Research Topics

Human movement and motor control in the natural environment

Edited by
Peter A. Federolf, Maurice Mohr, Gert-Jan Pepping, Thorsten Stein,
Steven van Andel and Gillian Weir

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Human movement and motor control in the natural environment

Topic editors
Peter A. Federolf — University of Innsbruck, Austria
Maurice Mohr — University of Innsbruck, Austria
Gert-Jan Pepping — Australian Catholic University, Australia
Thorsten Stein — Karlsruhe Institute of Technology (KIT), Germany
Steven van Andel — IJsselheem Foundation, Netherlands
Gillian Weir — New York Yankees, United States

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EDITED AND REVIEWED BY
Markus O. Heller,
University of Southampton,
United Kingdom

*CORRESPONDENCE
Maurice Mohr,
maurice.mohr@uibk.ac.at

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Editorial: Human movement and motor control in the natural environment

Maurice Mohr[1]*, Peter Federolf[1], Gert-Jan Pepping[2], Thorsten Stein[3], Steven van Andel[1,4] and Gillian Weir[5]

[1]Department of Sport Science, University of Innsbruck, Innsbruck, Austria, [2]School of Behavioural and Health Sciences, Australian Catholic University, Brisbane, QLD, Australia, [3]Institute of Sports and Sports Science, Karlsruhe Institute of Technology (KIT), Karlsruhe, Baden-Württemberg, Germany, [4]IJsselheem Foundation, Kampen, Netherlands, [5]New York Yankees, Tampa, FL, United States

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Editorial on the Research Topic
Human movement and motor control in the natural environment

Introduction

Studies in human movement science are typically motivated by the underlying goal to improve human performance and/or quality of life, e.g., through more efficient or effective training and rehabilitation of the movement system over the lifespan. While the respective experimental studies usually take place in laboratory environments, their conclusions and predictions are meant to inform training and rehabilitation in the real world, e.g., on the playing field, on the sidewalk, or at the work place. In the natural sciences, this is the traditional approach: we simplify problems so that we can design rigorous laboratory studies that follow the scientific method to then draw strong conclusions about the real world. In human movement science, however, simplifying the problem may more often than not lead to conclusions that are limited, if not invalid, outside of the laboratory, i.e., they lack ecological validity. This is because the human movement system has evolved in constant interaction with the highly complex, natural environment, which is often neglected in the simplified laboratory environment. As a result, any systematic assessment of the movement system must be a balance between creating conditions that allow to study an effect of interest while ensuring that the observed behavior is still relevant in the real world. With the advent of more advanced technologies to measure unconstrained human movement, tipping this balance towards the real world has become more feasible, however, the complexity of the obtained data often requires equally advanced analytical techniques. Maybe more importantly, advanced theoretical understanding is needed to still come to valid and valuable conclusions from real-world movement data.

This Research Topic was aimed at highlighting current research that improves our understanding of human movement and motor control in natural environments, i.e., where individuals, patients, athletes, or other groups of interest perform, explore, and interact under real-world conditions. This article Research Topic features 17 articles—thirteen original research articles, three reviews, and one theoretical article—spanning multiple Research Topic in human movement science, including motor control and motor competence assessment, motor learning and coaching, and new approaches for field-based assessments of movements in everyday life and sports. In over half of the original research articles, human movement was studied in out-of-the-laboratory settings with six studies including actual outdoor settings. The remaining five original research articles either inform future movement assessments in out-of-the-lab settings or expand our understanding of how motor development and changing environments affect the human movement system. The three review articles summarized combined evidence from laboratory-based and field-based investigations, while the theoretical article presented a system-theoretical model of human motor behavior. The remainder of this editorial will highlight specific findings of the included articles that best showcase how our current understanding of the human movement system may evolve or be challenged when studied out-of the lab in natural environments.

Motor control and competence assessment in natural environments

The two studies by Ng and Button and van Duijn et al. focused on the importance of assessing motor skills under ecologically-valid conditions. The report by van Duijn et al. dealt with aquatic motor skills and argued for the necessity of including open water education in water safety competence assessments. Based on two pilot studies, the authors showed that pool-based assessments may fall short in replicating the motor and cognitive skills needed by learners to prevent accidents in open water. The authors suggested that future assessment batteries for water safety competence should include open water environments wherever possible while ensuring learner safety. Similarly, the report by Ng and Button challenge the validity of traditional assessments of general motor competence in children because these assessments are based on isolated movement tasks (e. g., running, jumping, throwing) that are performed out-of-context. Instead, the authors proposed to use active video gaming technology to assess children's motor competence in virtual environments that better mirror the capacity of the movement system to perform in and interact with natural and changing environments. Ng and Button presented a new video game-based instrument for movement competence assessment and underscored its internal validity for measuring four underlying movement competence constructs, i.e., stability, object-control, locomotion, and dexterity.

With a specific focus on the movement stability construct, the original research article by Angulo-Barroso et al. investigated how landing movement strategies evolve with age in three to nine year-old children. The authors demonstrated that landing strategies were influenced by the age of the children but not the presence or absence of an unexpected additional task (e.g., run to the left) following landing. They concluded that at the age of 4-5 years old, children go through a critical development phase regarding landing strategies characterized by the integration of more precise feedforward control mechanisms to modulate landing joint stiffness. Further, they argued that targeted practice of landing at this age and within natural environments, such as playgrounds, may facilitate this development step and help reduce the risk of landing injury in the long-term.

The reports by Xie et al. and by Huang et al. investigated the interaction of the movement system with its environment during various locomotion activities. Xie et al. demonstrated the influence of surface compliance on ankle joint dynamics during walking; specifically, that the control system adjusts ankle joint stiffness according to the surface compliance to maintain gait stability. Huang et al. used principal component analysis to describe, quantify, and compare lower limb movement patterns between a range of everyday locomotion tasks in varying environments. Using a movement similarity score, the authors categorized movements into three clusters (C1: walking, running, sitting-down, C2: hopping, C3: turning). Movements within these clusters can be reconstructed through combining basic kinematic synergies shared across clusters and cluster-unique kinematic synergies indicative of a modular motor control strategy. The authors suggested that the presented analytical framework can facilitate the assessment of real-world locomotion skills with specific application in rehabilitation and treatment planning.

Motor learning and coaching

Articles in this category expanded our understanding of 1) how motor learning outcomes are influenced by the learning task, learning environment, and learning conditions, and 2) how classical views in the motor learning domain may not hold outside of the laboratory.

At the most basic level, Moriyama et al. used a virtual ball-kicking task to confirm that motor adaptation to visual inputs follows similar processes in the lower limb compared to what is well known for the upper limb. At a more translational level, two review articles by Zhao et al. and by Teraz et al. focused on cognitive aspects of motor learning in athletic and elderly populations. Specifically, Teraz et al. used a systematic review to investigate whether exercise interventions with added cognitive tasks, i.e., "motor-cognitive training," were more efficacious in improving mobility outcomes compared to exercising alone in elderly populations. They concluded that "motor-cognitive training"—particularly exergaming interventions—only lead to larger improvements in mobility than exercise alone when mobility assessments were based on multicomponent tasks such as the timed-up-and-go test rather than simple walking tasks. The authors assumed that this is due to higher ecological validity of multicomponent mobility tasks. In the athletic context, Zhao et al. systematically reviewed studies to assess the effect of video-based training on anticipation and decision-making in football. Based on ten included studies, the authors confirmed that football players demonstrate improved anticipation and decision-making during both standardized computer-based tests and during open play. Interestingly, the authors noted that video-based training for decision-making skills may be most effective if delivered in a "first-person perspective", trying to imitate the real-world, natural environment as closely as possible for the learner, e.g., through virtual reality.

Collins et al. as well as Magelssen et al. studied motor learning and coaching at the implementation level in field-based scenarios. The study by Magelssen et al. is a good example for the disconnect that may arise when applying laboratory-derived motor learning theories to real-world learning. The authors compared the effects of an interleaved practice scheme (learners frequently switch between different learning tasks) and blocked practice scheme (learners sequentially go through each learning task) on skiing speed in slalom ski racers. While laboratory-derived theories would predict that interleaved practice leads to better performance during the skill retention phase, this prediction could not be confirmed for real-world learning of a complex skiing task. Among others, the authors suggest the absence of the expected effect to result from the high skill level of their participants and the continuous nature of the skiing task, which is in contrast to the discrete skills typically studied in laboratory experiments. Finally, Collins et al. asked the unusual but innovative question of how motor learning evolves in the absence of a prescribed learning strategy, i.e., in the absence of a coach. Specifically, they studied learning practices in skateboarders who are used to perform and train in coach-free environments. The authors demonstrated that skateboarders utilize a broad range of learning strategies that can be connected to elements from different and often contrasting theories on effective motor learning (e.g., cognitive vs. ecological). The authors suggest that, rather than advocating for the use of one specific coaching approach, effective coaching should be guided by the needs and preferences of the learners. Studying behavior of performers in coach-free real-world environments can help inform the development of such learner-centered coaching approaches.

New approaches for field-based human movement assessments

Contributions in this section presented novel approaches to quantify and/or analyze human movement in natural environments either for everyday or sports activities. One of the most fundamental variables to quantify real-world human movement is walking speed. Reggi et al. tested the validity of a GNSS-based real time kinematic (RTK) receiver to measure walking speed in a real-world outdoor setting. The authors demonstrated that RTKs improve the validity of walking speed estimates over standard GNSS-based estimates given the ability of RTKs to cope with poor sky visibility. Going a step further, van Andel et al. and Sharma and Rombokas explored analytical approaches to investigate full-body motor control strategies during locomotion in natural environments based on inertial-sensor based motion capture. Sharma and Rombokas compared different approaches to assess the "complexity" of lower limb movements during various ambulatory conditions, such as walking forward and backward, sidestepping, and unconstrained navigating through indoor environments. The authors showed that a range of common approaches to asses "movement complexity," i.e., dimensionality, step-to-step variability, and non-linear measures of system dynamics, lead to different conclusions regarding "movement complexity" for most conditions. Practical recommendations were derived, including the suggestion to avoid the term "complexity" and use the specific term for the measured construct. Focusing on the dimensionality aspect of "movement complexity," van Andel et al. investigated the influence of the measurement system (optical vs. inertial motion capture) and analysis approach (group-based vs. individual) on the dimensionality and temporal structure of postural changes during walking. Specifically, they used a principal component analysis (PCA) to structure the full-body motion into "principal movements" (PMs) and determined the internal consistency of PM-related outcomes between measurement systems and analysis approaches. Based on a high internal consistency for all lower-order PMs, i.e., those PMs that explain >95% of the total movement variance, van Andel et al. concluded that full-body inertial motion capture is suitable for studying movement dimensionality and basic postural variations outside of the laboratory. Further, they provided recommendations for avoiding potential pitfalls when quantifying movement dimensionality from either group-based or individual-based analyses of walking data.

Following a similar data Research Topic and analysis approach, but with application in sports science, Debertin et al. presented a proof of concept for a new method to quantify technique in alpine skiing. Typically, the output of a PCA is data-driven, i.e., defined by the movement to be analyzed. Debertin et al. proposed a new analysis framework where the PCA output is tailored to yield principal component axes for the assessment of essential technique elements of downhill skiing. This was achieved by curating a PCA input data set that included extreme variations of those technique elements performed by expert skiing instructors. The authors confirmed that their analysis framework can successfully discriminate between downhill skiing techniques and skill levels underscoring the potential use of this approach in technique training in skiing and beyond. Staying within the realm of downhill skiing but motivated by injury prevention, Heinrich et al. presented a novel approach for estimating joint moments of the lower limb and lower back during turning maneuvers. Specifically, they presented a three-dimensional musculoskeletal skier model, which tracks experimental kinematic data of a turning maneuver in a forward dynamics optimization framework. Heinrich et al. demonstrated an accurate reconstruction of the experimental data and reported joint moments in physiologically feasible ranges. They highlighted several advantages of this optimization approach compared to the classical inverse dynamics approach for estimating joint moments, e.g., that the described framework only requires kinematic inputs but no information about external forces, which makes it a feasible approach for analyzing actual racing and training runs. Finally, Zandbergen et al. presented lower limb running mechanics over the course of a marathon using an inertial motion capture system. The authors described a regression-based approach to estimate impact-related variables (e.g., tibial acceleration) during running that have been corrected for the influence of running speed and stride frequency. Zandbergen et al. highlighted scenarios where the analysis of uncorrected impact-related variables could lead to invalid recommendations for runners trying to improve their technique.

Theoretical considerations

Last but not least, Petryński et al. offered theoretical insight regarding internal mechanisms of human motor behavior. Grounded in Nikolai Bernstein's fundamental work on motor control, the authors presented a system-theoretical model of motor behavior, including two sub-systems: an information processing sub-system (from sensory reception to motor execution) and a sub-system containing the associated functional and operational modalities. The presented model and the authors' arguments partially supported the motivation of this Research Topic: When studying the human movement system, its behavior can only be understood in its entirety if all information processing steps involved in a motor action—as they occur in natural environments—are considered or at least appreciated by the observer.

Summary and conclusion

This Research Topic combines original research findings from diverse experimental settings with theoretical considerations on the behavior of the human movement system in natural and real-world environments. The included articles highlight the versatility of the movement system when humans are navigating on varying surfaces and through varying environments. Its versatility may be the pinnacle feature of the human movement system and if motor competence assessments are to capture this central feature, they must be conducted under close to real-world conditions. Similarly, motor learning interventions are likely most effective when they target all perceptuo-motor integration modalities of the movement system needed to perform the task of interest, e.g., anticipation and decision-making in sports or multisensory perception in aging. Further, real-world motor learning should be guided by the preferences and needs of the individual learner and the real-world tasks and environments in which their learned activities take place. Finally, this Research Topic provided know-how on data Research Topic techniques (e.g., full-body inertial motion capture) and analysis protocols (e.g., principal component analysis) to assess the versatility and mechanics of the human movement system outside of the laboratory while avoiding potential pitfalls. In conjunction, this article Research Topic advances our understanding and skillset to study human movement and motor control in real-world environments and paves the way for more ecologically valid conclusions about how to improve human performance and quality of life.

Author contributions

MM wrote the first draft of the editorial. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

Author GW was employed by the New York Yankees.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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How Compliance of Surfaces Affects Ankle Moment and Stiffness Regulation During Walking

Kaifan Xie[1,2†], Yueling Lyu[1,2†], Xianyi Zhang[1,2] and Rong Song[1,2*]*

[1]Key Laboratory of Sensing Technology and Biomedical Instrument of Guangdong Province, Sun Yat-sen University, Guangzhou, China, [2]Guangdong Provincial Engineering and Technology Center of Advanced and Portable Medical Devices, Sun Yat-sen University, Guangzhou, China

Humans can regulate ankle moment and stiffness to cope with various surfaces during walking, while the effect of surfaces compliance on ankle moment and stiffness regulations remains unclear. In order to find the underlying mechanism, ten healthy subjects were recruited to walk across surfaces with different levels of compliance. Electromyography (EMG), ground reaction forces (GRFs), and three-dimensional reflective marker trajectories were recorded synchronously. Ankle moment and stiffness were estimated using an EMG-driven musculoskeletal model. Our results showed that the compliance of surfaces can affect both ankle moment and stiffness regulations during walking. When the compliance of surfaces increased, the ankle moment increased to prevent lower limb collapse and the ankle stiffness increased to maintain stability during the mid-stance phase of gait. Our work improved the understanding of gait biomechanics and might be instructive to sports surface design and passive multibody model development.

Keywords: ankle biomechanics regulations, EMG-driven musculoskeletal model, muscle excitations, compliant surfaces, gait analysis

Edited by:
Maurice Mohr, University of Innsbruck, Austria

Reviewed by:
Wenxin Niu, Tongji University, China
Elisabetta M. Zanetti, University of Perugia, Italy

****Correspondence:***
Xianyi Zhang
zhangxianyi@mail.sysu.cn
Rong Song
songrong@mail.sysu.edu.cn

†These authors have contributed equally to this work

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INTRODUCTION

The ankle joint plays several important roles such as shock absorption, stability, and propulsion in different subphases of the gait cycle, which can be realized by the regulations of ankle biomechanics (Robertson and Winter, 1980; Neptune et al., 2001). When environments change, the ankle joint adapts its biomechanical properties accordingly (Winter, 1995; Bayram and Bayram, 2018). These adaptions include the regulations of ankle moment and stiffness (Kepple et al., 1997; Whitmore et al., 2019). Ankle moment and stiffness are both regulated primarily by ankle muscles and can be regulated at different levels by co-activation of the agonist and antagonist muscles. For instance, enhanced activation of agonist and antagonist can increase the ankle stiffness while keeping the net ankle moment constant (Lee et al., 2014; Wind and Rouse, 2020).

In order to learn about the ankle moment and stiffness regulations, several methods have been developed to estimate ankle moment and stiffness. Ankle moment can be estimated from muscle forces and their associated moment arms (Sartori et al., 2012; Sartori et al., 2014). An inverse dynamics approach has been also used to estimate ankle moment by solving for the unknowns in the algebraic equations which take segmental anthropometry, lever arms, and movements measured as input (Vaughan and Christopher, 1996). The main sources of error in this approach are the inaccuracy in movement coordination data and estimations of body segment parameters (Riemer and Hsiao-Wecksler, 2008). Ankle stiffness is an important component of ankle impedance and can be estimated from the isolated angle and torque response to the perturbation applied to the ankle joint (Rouse et al., 2014; Lee and Hogan, 2015; Shorter and Rouse, 2018). In recent years, some perturbing robots have been developed to apply perturbations to the ankle joint in a certain period of the gait cycle. A majority of previous studies obtained joint stiffness from the slope of the joint moment–angle curve directly (Gunther and Blickhan, 2002; Yoon et al., 2007; Mager et al., 2018), which is referred to as quasi-stiffness (Latash and Zatsiorsky, 1993). However, due to the positive work produced by muscles during joint movements, quasi-stiffness is not a reasonable representation of joint stiffness (Rouse et al., 2013). An alternative way is to derive continuous ankle stiffness from the stiffness of constituent muscle–tendon units (MTU) using an EMG-driven musculoskeletal model (Sartori et al., 2015).

Previous studies demonstrated that ankle moment and stiffness were regulated according to the subphase of the gait cycle and walking environments. During the early stance phase, the ankle dorsiflexion moment is generated to provide preparation for weight acceptance. During the mid- and late stance phases, the ankle plantar flexion moment generated contributes to support and forward progression (Kepple et al., 1997; Sadeghi et al., 2001). The ankle stiffness increases from heel strike, reaching maximum in the late stance phase and then decreases to a low value before toe-off (Lee et al., 2016). This regulation of ankle stiffness matches with the need to prevent foot slap following heel strike and maintains stability during the stance phase (Lee et al., 2016). When the walking environment changes, the ankle moment and stiffness can be regulated to cope with the change (Ferris et al., 1998; Ferris et al., 1999; Yang and Pai, 2010; Whitmore et al., 2019; Yoo et al., 2019). For example, during the first exposure to a novel and unannounced slippery surfaces, ankle plantar flexion moments would reduce during the late stance phase for slippery recovery (Yang and Pai, 2010). When the swing limb was tripped by surface obstacles, larger ankle plantar flexion moment was generated on the supporting limb to provide adequate time and clearance for positioning of the recovery foot (Pijnappels et al., 2005). A recent study found that ankle stiffness decreased in the late stance phase while walking on a slippery surface to avoid falls (Whitmore et al., 2019). It has been shown that leg stiffness increased during the stance phase while running on more compliant surfaces, which may improve body stability on compliant surfaces (Ferris et al., 1998; Ferris et al., 1999). As leg stiffness primarily depends on the ankle joint stiffness (Farley and Morgenroth, 1999), increased leg stiffness on compliant surfaces may primarily result from the ankle stiffness.

Although many factors can affect the ankle moment and stiffness, it remains unclear how humans regulate them while walking on surfaces with different levels of compliance. Our study aimed to determine how humans regulate ankle moment and stiffness while walking on surfaces with different levels of compliance. As each subphase of gait has distinct biomechanical demands, we hypothesized that the compliance of surfaces may affect ankle moment and stiffness regulations in different subphases of a gait cycle. An EMG-driven musculoskeletal model was applied to estimate ankle moment and stiffness while walking on surfaces with different levels of compliance.

MATERIALS AND METHODS

Materials

Three materials were selected to form three surfaces for subjects to walk on. The materials selected were rubber, ethylene–vinyl acetate copolymer (EVA), and expandable polyethylene (EPE). The surface of the force plate made up of aluminum was another surface for subjects to walk on and its elastic modulus was about 70,000 MPa. A universal material testing machine was used to obtain the force deformation data of the samples of the materials. The thickness of the samples was 5 cm. Then the elastic modulus of materials was obtained from the relationship of stress and strain (0–300 kPa). The relationship of stress and strain is shown in **Supplementary Figure 1**. The elastic modulus of rubber, EVA, and EPE was 4.10, 0.34, and 0.29 MPa, respectively.

Experiment Setup

Subjects were required to walk barefoot during the experiment. Before starting walking trials on one surface, subjects were required to walk on this surface to adapt to it. One static pose trial was performed before walking trials. Then subjects were required to perform four walking trials on each surface. In walking trials, subjects were required to walk across a walkway of a length of 4.5 m in 4–5 s. The subjects were allowed to take a 1-min rest between each pair of successive walking trials and a 15-min rest when the surfaces for walking trials needed to be changed. One subject was recruited for the pilot study, and the ankle stiffness estimates were obtained using an EMG-driven musculoskeletal model. Effect sizes [Cohen's f (Cohen, 1969)] of the ankle stiffness estimated during mid- and late stance phases in the pilot study were greater than those obtained using 1.5. Software G*power used for sample size calculation. As a result, the sample size required was eight for repeated measures ANOVA with an effect size f value of 1.5, an α value of 0.05, and a power value of 0.8. Then ten healthy subjects (male, 63.46 ± 7.73 kg, 23.20 ± 1.54 years old) without lower extremity injury participated in the experiment. All subjects signed the informed consent form before participating in the experiment. This study was approved by the School of Medicine, Sun Yat-sen University Institutional Review Board, on March 1, 2021.

Recordings of walking trials included the whole stance phase of the subjects' right leg. EMG data were collected from four ankle muscles: tibialis anterior (TA), soleus (SOL), gastrocnemius lateralis (GAL), and gastrocnemius medialis (GAM). EMG data were recorded at 1,500 Hz using a telemetered EMG system (Noraxon, Scottsdale, USA). Electrodes were placed on these muscles using surface EMG for non-invasive assessment of muscles (SENIAM) guidelines. (Details are available at http://www.seniam.org/) GRF data were recorded at 1,500 Hz using a force plate (Kistler, Winterthur, Switzerland). Each subject had 30 retroreflective markers placed on their body during the experiment. The retroreflective markers were placed on the trunk, pelvis, and left and right extremities. The placements of retroreflective markers are shown in **Supplementary Figure 2**. Marker trajectories were recorded at 100 Hz using a 6-camera motion capture system (Motion Analysis Corporation, Santa

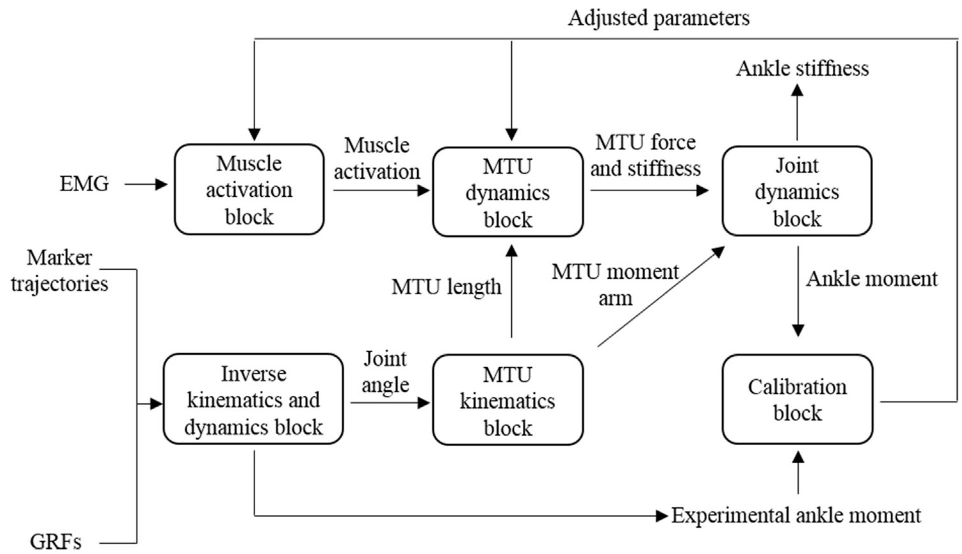

FIGURE 1 | Schematic structure of electromyography (EMG)-driven musculoskeletal model.

Rosa, USA). EMG, GRFs, and marker trajectories were all collected synchronously.

EMG-Driven Musculoskeletal Model

The schematic structure of an EMG-driven musculoskeletal model for ankle moment and stiffness estimation is shown in **Figure 1**, similar to the model proposed by Sartori et al. (2015). The EMG-driven musculoskeletal model includes six blocks.

In the muscle activation block, raw EMG data were band-pass–filtered (30–450 Hz), full-wave–rectified, and low-pass–filtered (6 Hz) using a zero-phase second-order Butterworth filter. For each subject and muscle, the resulting EMG linear envelopes were normalized to the maximum processed values obtained from all recorded trials. The processed and normalized EMG signals would be referred to as excitations. Muscle excitations were subsequently processed using a recursive filter to model the twitch response of the muscle fibers to the excitation onset. The filter used was given by Lloyd and Besier (2003):

$$u(t) = \alpha e(t-d) - \beta_1 u(t-1) - \beta_2 u(t-2), \tag{1}$$

where $u(t)$ is the neural activation and d is the electromechanical delay, and a set of constrains were employed given as follows:

$$\begin{cases} \beta_1 = C1 + C2 \\ \beta_2 = C1 \cdot C2 \\ \alpha - \beta_1 - \beta_2 = 1.0 \end{cases}, \tag{2}$$

where $|C1|<1$ and $|C2|<2$. The values of $C1$ and $C2$ changed the impulse response of the filter.

Then a non-linear transfer function was used to account for the non-linearity in the excitation-to-force relationship and obtain the resulting muscle activation (Lloyd and Besier, 2003):

$$a(t) = \frac{e^{Au(t)} - 1}{e^{A} - 1}, \tag{3}$$

where $a(t)$ is the muscle activation and A is the non-linear shape factor.

In the inverse kinematics and dynamics block, marker positions recorded from the static pose trials were used to scale a generic model of the human musculoskeletal geometry to match each subject's anthropometry in OpenSim. Joint angles were calculated using marker trajectories from walking trials *via* the inverse kinematics (IK) tool. Ground reaction forces (GRFs) and the results of IK were then used to calculate ankle moment τ_{ID} *via* the inverse dynamics (ID) tool. Ankle moment obtained by this way would be referred to as experimental ankle moment.

The MTU kinematics block received joint angles from the inverse kinematics tool in OpenSim. The MTU lengths and moment arms derived from the scaled model in OpenSim were used to create polynomial fitting functions. These functions described how each MTU length and moment arm change with respect to joint angles (Menegaldo et al., 2004). With these polynomial fitting functions and IK-generated joint angles, time-varying MTU lengths and moment arms in walking trials could be obtained.

The MTU dynamics block took muscle activation and MTU lengths from previous blocks as input. A hill-type muscle model was used to estimate the instantaneous muscle fiber length and force and series elastic tendon strain and force for each MTU (Hill et al., 1938; Zajac, 1989; Hoy et al., 1990):

$$F_m = F_{max}\left[f\left(\tilde{l}_m\right)f\left(\tilde{v}_m\right)a + f_P\left(\tilde{l}_m\right)\right], \tag{4}$$

$$F_t = \begin{cases} 0, & \varepsilon \le 0 \\ 1480.3F_{max}\varepsilon^2, & 0 < \varepsilon \le 0.0127 \\ (37.5\varepsilon - 0.2375)F_{max}, & \varepsilon \ge 0.0127 \end{cases}, \tag{5}$$

$$\varepsilon = \frac{l_t - l_{st}}{l_{st}}, \quad (6)$$

$$F_{mt} = F_t = F_m cos\Phi, \quad (7)$$

where F_m is the fiber force; F_t is the tendon force; F_{mt} is the MTU force; F_{max} is the maximum isometric muscle force; $f(\tilde{l}_m)$ and $f(\tilde{v}_m)$ are the active force–length relationship (Giat et al., 1994) and force–velocity relationship (Schutte and Rodgers, 1993), respectively; $\tilde{l}_m$ is the fiber length normalized to the optimal fiber length l_{m0}; $\tilde{v}_m$ is the ratio of current muscle fiber velocity to the maximum contraction velocity; a is the muscle activation; $f_P(\tilde{l}_m)$ is the passive elastic force–length relationship (Buchanan et al., 2004); l_t is the current tendon length; l_{st} is its slack length; and Φ is the pennation angle.

Muscle fiber stiffness K_m is calculated as the partial derivative of fiber force F_m with respect to the fiber length l_m:

$$K_m = \frac{\partial F_m}{\partial l_m}. \quad (8)$$

K_t is defined by the slope of the force–strain curve of tendon as follows:

$$K_t = \frac{d F_t}{d l_t}. \quad (9)$$

The MTU stiffness could be modeled as the muscle fiber stiffness K_m in series with the tendon stiffness K_t as follows:

$$K_{mt} = \left(\frac{1}{K_m} + \frac{1}{K_t}\right)^{-1}. \quad (10)$$

The joint dynamics block computed ankle moment and stiffness. Ankle moments were calculated as the product of each MTU force and their associated moment arms, as follows:

$$\tau_{EMG} = \sum_{i=1}^{\#MTU} F_{mt_i} \cdot r_i, \quad (11)$$

where τ_{EMG} is the ankle moment, F_{mt_i} is the force of the ith MTU, and r_i is the moment arm with respect to the ankle joint of ith MTU.

Using the estimated muscle forces and the MTU stiffness, the corresponding ankle stiffness K_{ankle} was computed as follows (McIntyre et al., 1996):

$$K_{ankle} = \sum_{i=1}^{\#MTU} K_{mt_i} \cdot r_i^2 + \frac{\partial r_i}{\partial \theta} \cdot F_{mt_i}, \quad (12)$$

where K_{mt_i} is the stiffness of the ith MTU, r_i is the moment arm with respect to the ankle joint of ith MTU, θ is the ankle joint angle, and F_{mt_i} is the force of the ith MTU.

The calibration block determined subject-specific parameters for the EMG-driven musculoskeletal model. Some parameters were adjusted through the calibration process within moderate bounds so that joint moments calculated from MTU forces and moment arms in joint dynamics block could be closer to the joint moments

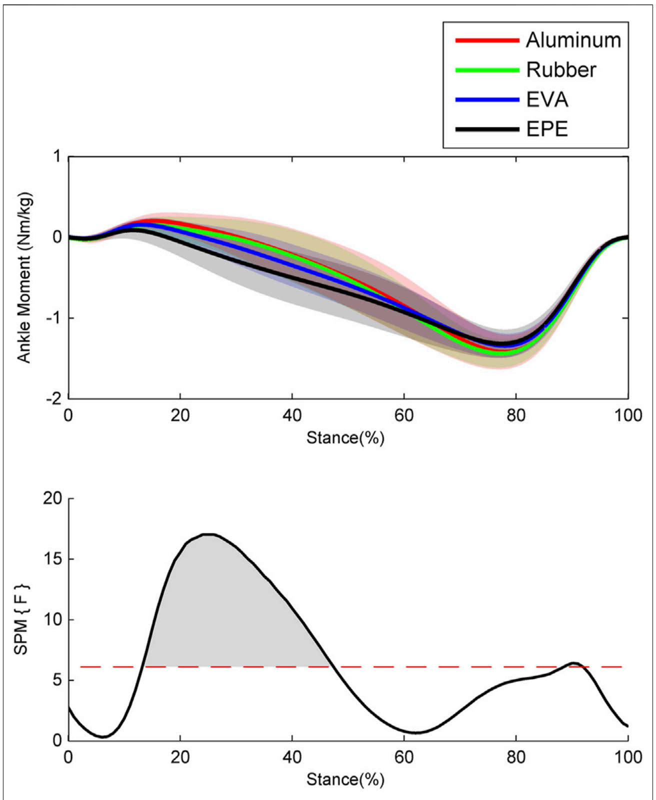

FIGURE 2 | Ensemble average curves (continuous line) and standard deviation (shaded area) for ankle moment during walking. The positive values indicate dorsiflexion moment, and the negative values indicate plantar flexion moment. Data are reported for the stance phase of walking with 0% being heel strike and 100% being toe-off events. The shaded areas in the SPM figure indicate that a significant difference was found (p < 0.05) during this period.

calculated *via* ID in the inverse kinematics and dynamics block. The optimization formulation is listed as follows:

$$J = \frac{1}{N}\sum_{i=1}^{N} (\tau_{EMG}(i) - \tau_{ID}(i))^2, \quad (13)$$

where N represented the length of the data used for the calibration. The Nelder–Mead algorithm was used to minimize the objective function J. The input parameters of the calibration block and their bounds are as follows: $C1$ and $C2$ in the muscle activation block, which varied between −1 and 1; A in the muscle activation block, which varied between −3 and 0; F_{max} in the MTU dynamics block were adjusted by strength coefficients γ_1 and γ_2 for ankle dorsi flexors and ankle plantar flexors, respectively, and γ_1 γ_2 varied between 0.5 and 1.5; and in the MTU dynamics block, the optimal muscle fiber length was adjusted so that l_{m0} = initial value ± 2.5% and the tendon slack length were adjusted so that l_{st} = initial value ± 5%. The initial F_{max}, l_{m0}, and l_{st} were obtained from the scaled model in OpenSim. The calibration process was conducted because some parameters of MTU were different among individuals. Using a calibration process, the parameters could be adjusted to individual values.

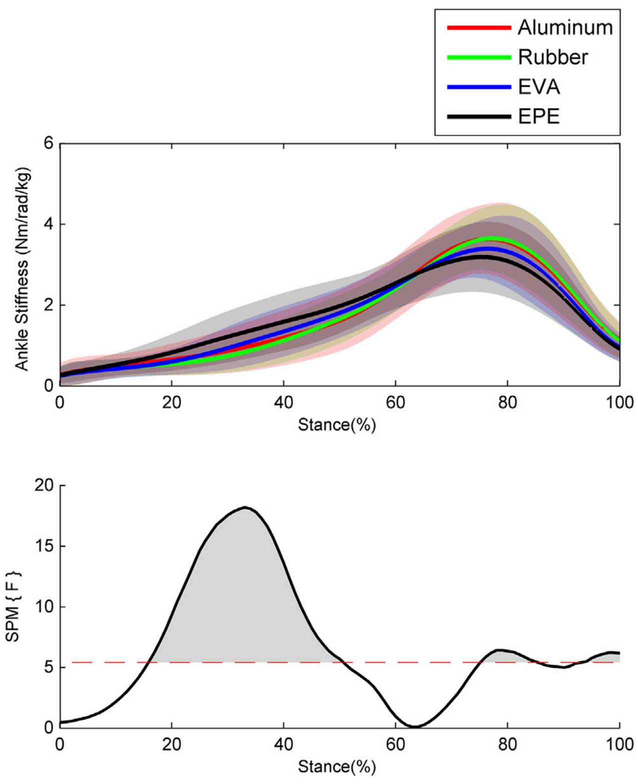

FIGURE 3 | Ensemble average curves (continuous line) and standard deviation (shaded area) for ankle stiffness during walking. Data are reported for the stance phase of walking with 0% being heel strike and 100% being toe-off events. The shaded areas in the SPM figure indicate that significant difference was found ($p < 0.05$) during this period.

Data Analysis

Walking speeds were calculated from the marker placed on the seventh cervical vertebra of subjects. The ankle moment and stiffness were estimated from the recorded GRFs, EMG, and marker trajectories *via* the EMG-driven musculoskeletal model. Similarity between τ_{EMG} in the joint dynamics block and the experimental ankle moment in the inverse kinematics and dynamics block after calibration was calculated using the root mean squared error normalized with respect to the root mean squared sum of the corresponding experimental ankle moment (NRMSE) of each subject.

The presence of significant differences among surfaces in ankle moment, ankle stiffness, GRFs, and muscle excitations was assessed with 1D statistical parametric mapping (SPM). SPM represented the convergence of change distribution analysis and significance probability mapping (Friston et al., 1994). One-way repeated measure ANOVA of 1D SPM was performed using an open-source code in MATLAB (MatlabR 2014a, MathWorks Inc., Natick, USA). Details of the SPM analysis and the code are available at https://spm1d.org/.

RESULT

The mean (standard deviation) speeds of walking trials on force plate, rubber, EVA, and EPE surfaces were 0.90 (0.06), 0.90 (0.05), 0.88 (0.05), and 0.89 (0.05) m/s, respectively. The mean (standard deviation) NRMSE of ten subjects showing similarity between τ_{EMG} and experimental ankle moment was 0.353 (0.043).

The ankle moments calculated *via* ID in OpenSim are shown in **Figure 2**. During the early stance phase around the 0–20% of stance phase, ankle moments on surfaces with higher compliance were smaller and changed from dorsiflexion to plantar flexion earlier. During the 30–47% of stance phase where ankle moments on all four surfaces have changed into plantar flexion, ankle moments increased as compliance of walking surfaces increased within the force plate, EVA, and EPE surfaces ($p < 0.001$, effect size *f*: 0.27–0.48). During the late stance phase, almost no significant difference existed in ankle moments. During the whole stance phase, ankle moments remained almost the same while walking on the force plate and rubber surfaces.

Results of the ankle stiffness are shown in **Figure 3**. During the 40–50% of stance phase, the ankle stiffness increased as compliance of surfaces increased within the force plate, EVA, and EPE surfaces ($p < 0.001$, effect size *f*: 0.22–0.28), while this trend reversed during the 76–85% ($p = 0.023$, effect size *f*: 0.20–0.23) and 94–100% ($p = 0.035$, effect size *f*: 0.21–0.25) of stance phase. Similar to the pattern of ankle moment, the ankle stiffness on the force plate and rubber surface remained almost the same during the whole stance phase.

Results of GRFs and muscle excitations are shown in **Figure 4** and **Figure 5**, respectively. During the 10–19% of stance phase, vertical GRF on the most compliant surface EPE was larger than that on the other three surfaces ($p < 0.001$, effect size *f*: 0.26–0.34). During the 60–91% of stance phase, vertical GRF decreased as compliance of surfaces increased within the force plate, EVA, and EPE surfaces ($p < 0.001$, effect size *f*: 0.42–0.59). As for anterior-posterior GRF, significant difference existed during the 15–25% ($p = 0.001$, effect size *f*: 0.27–0.31) and 64–69% ($p = 0.016$, effect size *f*: 0.28–0.34) of stance phase. Anterior-posterior GRF on the EPE surface was larger than GRF on the other three surfaces during the 15–25% of stance phase. No obvious trend occurred in anterior–posterior GRF among surfaces during the 64–69% of stance phase. GRFs in both directions remained almost the same on the force plate and rubber surfaces during the stance phase. Excitations of SOL and GAL on EPE surface were significantly larger than other surfaces during the early stance phase ($p = 0.006$, effect size *f*: 0.18–0.27 and $p = 0.001$, effect size *f*: 0.24–0.38, respectively). Peak excitations of SOL and GAM tended to decrease as compliance of walking surfaces increased within the force plate, EVA, and EPE surfaces, although no significant difference existed (SOL: effect size $f = 0.17$ at 17% of the stance phase; GAM: effect size $f = 0.29$ at 59% of the stance phase).

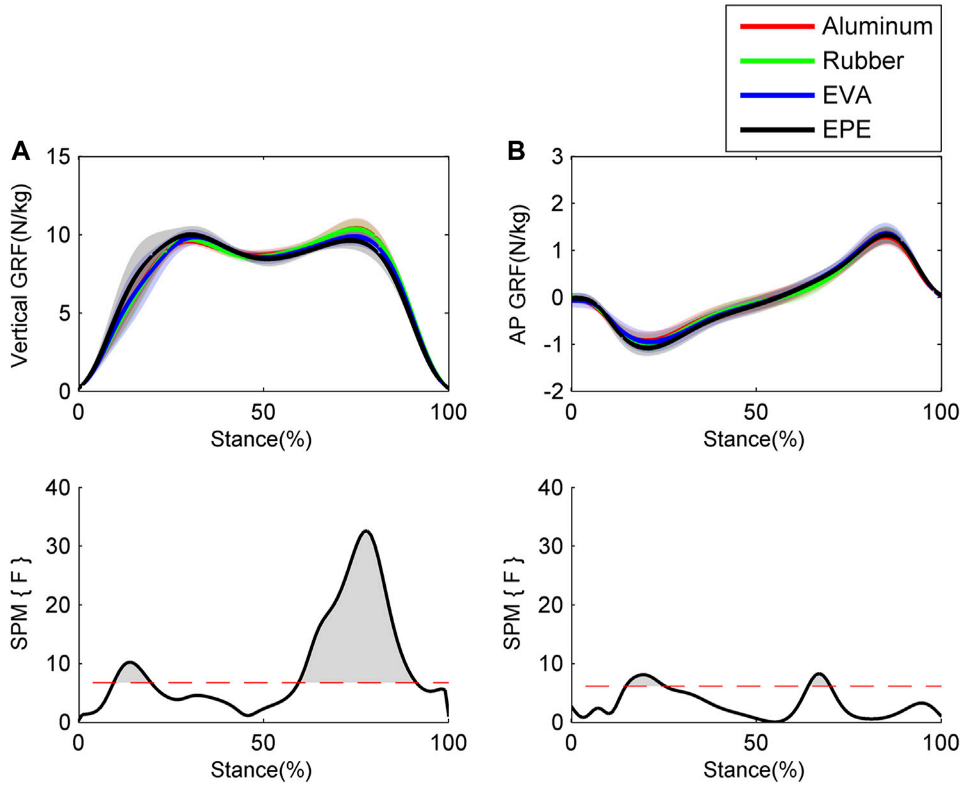

FIGURE 4 | Ensemble average curves (continuous line) and standard deviation (shaded area) for GRFs during walking: **(A)** vertical GRF; **(B)** anterior–posterior (AP) GRF. Data are reported for the stance phase of walking with 0% being heel strike and 100% being toe-off events. The shaded areas in the SPM figure indicate that significant difference was found ($p < 0.05$) during this period.

DISCUSSION

In this study, subjects were required to walk on surfaces with four levels of compliance. Time-varying ankle moment and stiffness were estimated from GRFs, EMG, and three-dimensional reflective marker trajectories during the whole stance phase *via* an EMG-driven musculoskeletal model. Two main findings in our results were that 1) surface compliance affected the regulations of the ankle moment and stiffness and 2) the effect of the surfaces compliance on ankle moment and stiffness regulations varied in different subphases.

Surface compliance had different effects on ankle moment regulations during the early and mid-stance phases. During the early stance phase, the ankle dorsiflexion moment is a preparation for weight acceptance and provides a deceleration of the foot when landing (Gray and Basmajian, 1968; Hunt et al., 2001). Reduced dorsiflexion moments were observed when the heel stroke on surfaces with increased compliance due to the better cushioning property of these surfaces. During the mid-stance phase, larger ankle plantar flexion moments were generated on surfaces with increased compliance to prevent lower limb collapse, improving upper body support and stability (Winter, 1980; Kepple et al., 1997; Sadeghi et al., 2001). As almost no difference in the vertical and anterior–posterior GRFs among surfaces was found during this subphase, the larger ankle plantar flexion moment observed on surfaces with increased compliance might be due to larger moment arms. While walking on surfaces with increased compliance, the plantar center of pressure (COP) might advance more quickly to reach the full foot contact earlier in order to maintain stability (Zhang and Li, 2014). Thus, the distance between the COP and the ankle joint center enlarged, resulting in larger moment arm and ankle plantar flexion moment during the mid-stance phase. During the late stance phase, the ankle plantar flexion moment contributes to the forward acceleration (Kepple et al., 1997). Forward accelerations might be similar among surfaces as walking speeds were kept similar, which may explain why there was no difference in ankle moments during this subphase (Peterson et al., 2010; Peterson et al., 2011).

Ankle stiffness regulations in response to surface compliance were different between the mid- and late stance phases. During the mid-stance phase, the ankle stiffness increased with the increase in surfaces compliance, which was consistent with the leg stiffness regulations while running on compliant surfaces (Ferris et al., 1998). It has been shown that larger leg stiffness while running on compliant surfaces helped to keep the vertical location of the center of mass (COM) the same as that on rigid surfaces, allowing humans to maintain steady gait on different surfaces (Ferris et al., 1998; Ferris et al., 1999). Computer simulation showed that the leg stiffness depended on the

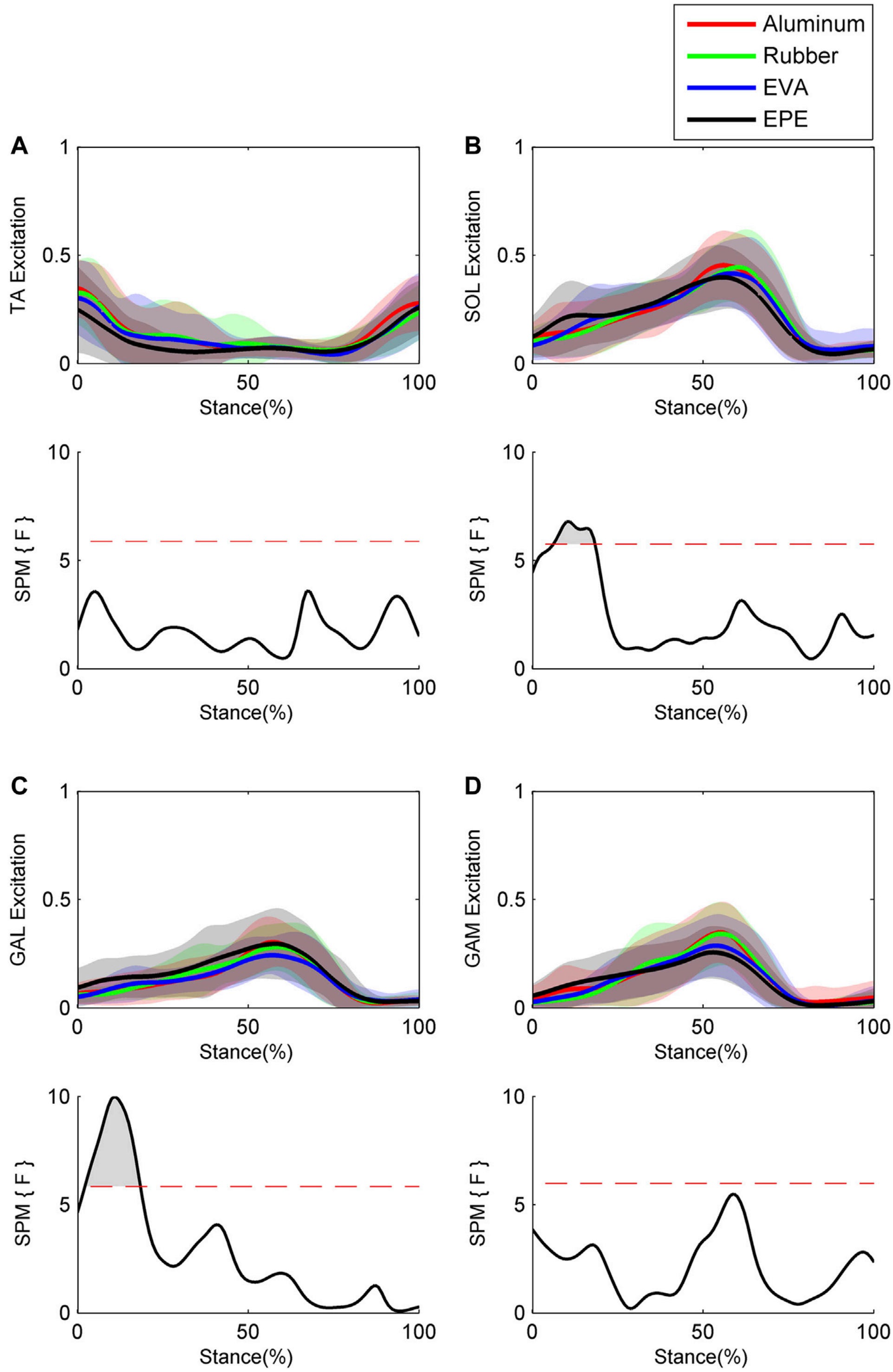

FIGURE 5 | Ensemble average curves (continuous line) and standard deviation (shaded area) for muscle excitation during walking: **(A)** tibialis anterior (TA); **(B)** soleus (SOL); **(C)** gastrocnemius lateralis (GAL); and **(D)** gastrocnemius medialis (GAM). Data are reported for the stance phase of walking with 0% being heel strike and 100% being toe-off events. The shaded areas in the SPM figure indicate that a significant difference was found ($p < 0.05$) during this period.

joint stiffness of the lower limb, especially the ankle stiffness (Farley et al., 1998; Farley and Morgenroth, 1999). It should be noted that previous studies only calculated the average leg stiffness of the whole stance phase (Ferris et al., 1998; Ferris et al., 1999), while our study estimated the time-varying ankle stiffness during the whole stance phase and found that higher compliance of surfaces increased ankle stiffness during the mid-stance phase, but that decreased during the late stance phase. Our results showed that ankle stiffness increased only during the mid-stance phase on compliant surfaces, which may lead to efficient gait as increased ankle stiffness during the whole stance phase required higher energy cost (Moore et al., 2014; Li et al., 2021).

Previous studies have shown that alterations in ankle muscle excitations can change ankle stiffness (Trevino and Lee, 2018; Whitmore et al., 2019; Wind and Rouse, 2020). Our results showed that excitations of SOL and GAL on the surface with the lowest level of compliance were significantly larger than those on the other three surfaces during the early stance phase, which is consistent with that ankle plantar flexion muscle excitations increased following stepping on compliant surfaces (Marigold and Patla, 2005). As there was an electromechanical delay, the increased muscle excitations on compliant surfaces during the early stance phase might contribute to the larger ankle stiffness during the mid-stance phase (Lloyd and Besier, 2003). Our results also showed that during the late stance phase, peak excitations of SOL and GAM increased as compliance of walking surfaces decreased (no significant difference existed), while peak excitation of GAL showed no such trend. Increased peak excitations of SOL and GAM might contribute to the increase in peak ankle stiffness during the late stance phase as they are two of the major ankle plantar flexors (Wickiewicz et al., 1983; Silver et al., 1985).

The elastic modulus of materials reported in the Materials and Methods was obtained from the relationship of stress and strain (0–300 kPa), and this value was comparable between the EVA and EPE. It should be noticed that these two materials had a non-linear mechanical behavior. If we took only the part of the relationship of stress and strain into account, where stress is below 30 kPa, the obtained elastic modulus (0–30 kPa) of the EVA was more than twice of the EPE (0.25 and 0.10 MPa, respectively). Thus, the compliance of EVA and EPE was quite different during the initial contact with surfaces, probably leading to the difference in ankle moment and stiffness between two surfaces.

Alterations in the ankle moment and stiffness were found in the rubber, EVA, and EPE surfaces, and it is notable that both ankle moments and ankle stiffness remained almost the same while walking on the force plate and rubber surfaces. This might be associated with the mechanical properties of human tissues. The elastic modulus of plantar tissue is about 0.7 MPa (Ledoux and Blevins, 2007), while this value of the EVA and EPE was 0.34 and 0.29 MPa, respectively. The EVA and EPE are softer than plantar tissue, and the deformation during gait mainly occurred on the walking surfaces. The elastic modulus of the force plate and rubber was about 70000 and 4.10 MPa, respectively, which was significantly larger than the plantar tissue. Hence, the deformation during gait primarily occurred on the plantar tissue while walking on them. As the vertical GRF remained almost the same on the force plate and rubber surfaces during the whole stance phase, similar deformation occurred on plantar tissue, leading to similar ankle moment and stiffness regulations (Ferris et al., 1999). There are some limitations in this study. The tested order of different surfaces was not randomized, which may have an influence on the results. However, subjects were given time to familiarize with the tested surface before recording and took a 15-min rest between two surface conditions. This adapting practice and rest between two conditions can minimize the effect of previous walking trials on other surfaces. The effect sizes f of differences in the ankle moment and stiffness were considered medium in this study (Cohen, 1969), which is lower than the calculated value of the pilot study. As such, the results might be considered as exploratory. Step length and stride frequency were not strictly controlled in our experiment, which may have an effect on the values of GRFs and ankle moments (Allet et al., 2011). Only four superficial muscles were monitored and taken into account in the model to calculate ankle stiffness, leading to lower ankle stiffness estimates as the contributions of deeper muscles were neglected.

The ankle joint plays a key role in adjusting leg mechanics to adapt to alterations in surface properties (Ferris et al., 1998; Zanetti et al., 2013; Kessler et al., 2020). Our findings about ankle mechanical adaptations could be instructive to the sport surface design (Zanetti et al., 2013). Joint stiffness is one of the key parameters to develop passive multibody models for human body simulations (Pascoletti et al., 2019, 2020). Our findings provided ankle stiffness information for the construction of human simulation models on surfaces with different compliance.

CONCLUSION

Our study provides insights into how humans regulate ankle moment and stiffness during the whole stance phase while walking on surfaces with different levels of compliance. Surfaces with higher levels of compliance increased the ankle plantar flexion moment and stiffness during the mid-stance phase, while decreased the ankle stiffness during the late stance phase. The ankle moment and stiffness regulations in response to surface compliance primarily helped to prevent lower limb collapse and improve stability on surfaces with different compliance. Our work gave a comprehensive understanding about the regulations of ankle biomechanics including ankle moment and ankle stiffness and might be instructive to sports surfaces design and passive multibody model development.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the School of Medicine, Sun Yat-sen University Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

KX and YL collected the data. KX and YL analyzed the data and drafted the manuscript. XZ and RS revised and determined the final manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbioe.2021.726051/full#supplementary-material

Supplementary Figure 1 | Stress–strain curves of three materials.

Supplementary Figure 2 | Marker placements on body of subjects, modified based on the marker set of gait2392 model in OpenSim.

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Characterization and Categorization of Various Human Lower Limb Movements Based on Kinematic Synergies

Bo Huang, Wenbin Chen, Jiejunyi Liang, Longfei Cheng and Caihua Xiong**

State Key Laboratory of Digital Manufacturing Equipment and Technology, Institute of Rehabilitation and Medical Robotics, Huazhong University of Science and Technology, Wuhan, China

A proper movement categorization reduces the complexity of understanding or reproducing human movements in fields such as physiology, rehabilitation, and robotics, through partitioning a wide variety of human movements into representative sub-motion groups. However, how to establish a categorization (especially a quantitative categorization) for various human lower limb movements is rarely investigated in literature and remains challenging due to the diversity and complexity of the lower limb movements (diverse gait modes and interaction styles with the environment). Here we present a quantitative categorization for the various lower limb movements. To this end, a similarity measure between movements was first built based on limb kinematic synergies that provide a unified and physiologically meaningful framework for evaluating the similarities among different types of movements. Then, a categorization was established *via* hierarchical cluster analysis for thirty-four lower limb movements, including walking, running, hopping, sitting-down-standing-up, and turning in different environmental conditions. According to the movement similarities, the various movements could be divided into three distinct clusters (cluster 1: walking, running, and sitting-down-standing-up; cluster 2: hopping; cluster 3: turning). In each cluster, cluster-specific movement synergies were required. Besides the uniqueness of each cluster, similarities were also found among part of the synergies employed by these different clusters, perhaps related to common behavioral goals in these clusters. The mix of synergies shared across the clusters and synergies for specific clusters thus suggests the coexistence of the conservation and augmentation of the kinematic synergies underlying the construction of the diverse and complex motor behaviors. Overall, the categorization presented here yields a quantitative and hierarchical representation of the various lower limb movements, which can serve as a basis for the understanding of the formation mechanisms of human locomotion and motor function assessment and reproduction in related fields.

Keywords: categorization, lower limb, locomotion, kinematic coordination, principal component analysis, cluster analysis, rehabilitation, robotics

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*Peter A. Federolf,
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*Arturo Forner-Cordero,
University of São Paulo, Brazil
Yaodong Gu,
Ningbo University, China*

****Correspondence:***
*Jiejunyi Liang
jjy_liang@hust.edu.cn
Caihua Xiong
chxiong@hust.edu.cn*

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INTRODUCTION

The human lower limb shows extraordinary motor ability in daily living, which is indispensable for humans in independent living. Through flexible use of the lower limb, humans can move in various gait styles and interact with diverse environmental conditions to cope with different requirements of activities of daily living. In the past, to understand, imitate, repair, or enhance the motor ability of the human lower limb, a lot of research has been done (Tucker et al., 2015; Young and Ferris, 2017; Koyama and Yamauchi, 2018; Price et al., 2019; Yao et al., 2019; Sun et al., 2020; Rodriguez-Fernandez et al., 2021). However, the enough motor dexterity of the human lower limb, as indicated by the diversity of their movement styles, brings challenges to the study of the lower limb movements. In this context, it can be predicted that the complexity of this challenging problem can be reduced by building a categorization for the wide variety of lower limb movements, which can partition the many lower limb movements into a series of small, representative, and homogenous sub-motion categories based on their similarities or differences.

Partitioning or categorization of the lower limb movements is useful in several fields (Papageorgiou et al., 2019; Schambra et al., 2019; Stival et al., 2019). In physiology, it can provide new insights into understanding the formation mechanisms of the lower limb movements. The formation of a category consisting of many different movements can uncover several similar control strategies employed by these movements in the category, which can help clarify whether there exist conserved control strategies across the various movements. In contrast, some potential mechanisms underlying the flexibility and plasticity of the human motor system can also be uncovered by the finding and comparison of different categories. In rehabilitation, a categorization can facilitate the assessment of motor function by subdividing the many movements into a few meaningful and manageable sub-motion categories and can avoid the risk of neglecting some important categories that have an impact on the assessment and subsequent rehabilitation treatments. Meanwhile, such categorization can also allow us to customize a standardized rehabilitation program for each category in order to achieve better treatment outcomes. In robotics, a categorization can promote the development of artificial limbs imitating or enhancing human motor ability (e.g., prostheses and exoskeletons). The categories and their movement characteristics can provide references for comparing the performance of the artificial limbs with the human limb, thereby encouraging the development of better mechanical or control systems. In practice, motivated by the advantages of the categorization, researchers have built different taxonomies or classification systems for different types of human movements, such as the taxonomies of hand grasps (Feix et al., 2016; Stival et al., 2019), whole-body support poses (Borras et al., 2017), and activities of daily living of upper limb (Gloumakov et al., 2020a; Gloumakov et al., 2020b), and the classification systems of normal walking (Vardaxis et al., 1998; Simonsen and Alkjaer, 2012), normal running (Liebl et al., 2014; Phinyomark et al., 2015), and pathological walking or running (Kuntze et al., 2018; Jauhiainen et al., 2020). However, to our knowledge, a quantitative categorization for the various lower limb movements has not been established to date. Given the diversity of human gait modes and interaction styles with the external environment, there are several questions that remain to be resolved for establishing the categorization: which movements are similar to each other and how to quantify the similarities among different types of lower limb movements.

To measure the similarity between movements, a key question is to select unified, informative, and quantitative movement descriptors which can characterize the various lower limb movements. In previous studies, to identify the subsets or categories underlying human gaits, the nature of gaits is usually described by some discrete gait parameters (Vardaxis et al., 1998; Mulroy et al., 2003; Simonsen and Alkjaer, 2012; Jauhiainen et al., 2020), such as phasic, spatiotemporal gait parameters (e.g., speed, stride length, cadence, and duty factor), or some critical kinematic and kinetic parameters (e.g., peak joint angles, moments, and powers, or joint angles, moments, and powers at specific events or phases in walking or running gaits). For example, walking and running, the terminologies describing the two most common lower limb movement modes, are usually differentiated by the duty factor (the fraction of the stride duration when each foot is on the ground) (Kram et al., 1997; Segers et al., 2006; Fihl and Moeslund, 2007). Likewise, through examining the similarity of kinematic and kinetic parameters, more than one category requiring different movement strategies has also been identified in normal walking, rather than only a single normative template of walking pattern as is often assumed (Vardaxis et al., 1998; Simonsen and Alkjaer, 2012). Without a doubt, these gait descriptors have provided a good basis for distinguishing walking or/and running gaits. However, only partial information is provided by these gait descriptors, which may obscure many other subtle features underlying the human lower limb movements (Kuntze et al., 2018; Sawacha et al., 2020). Moreover, part of the movement descriptors are suitable for characterizing walking and running but not for some other lower limb movements achieved by humans (e.g., sit-to-stand and turning in place) (Vardaxis et al., 1998; Etnyre and Thomas, 2007; Prakash et al., 2018).

In particular, studies in the field of motor control show that the many joint motions in the process of the limb movements are not independent of each other but constrained by the nervous system (Borghese et al., 1996; St-Onge and Feldman, 2003; Grillner and El Manira, 2020), which cannot be uncovered by the discrete and independent gait parameters mentioned above. Specifically, to generate a complex behavior, the joint motions are coordinated by the nervous system to bend or stretch together as several basic units or synergies. Then, the complex behavior can be constructed rapidly and efficiently through the combination of a small number of synergies. Inspired by the existence of the synergies, it can be argued that it is necessary to consider the coordination among joints when characterizing the lower limb movements, rather than only considering the characteristics of individual joints separately. More importantly, the joint synergies have been found in different lower limb movements, including various cyclical and non-cyclical movements (e.g., squats, walking, going up or down a step, and running) (St-Onge and Feldman, 2003; Hicheur et al., 2006; Moro et al., 2012). Similarly, a planar covariation law of intersegmental coordination is also found in human locomotion (Borghese et al., 1996; Ivanenko et al., 2007), where the temporal changes in the elevation angles of lower limb segments (thigh, shank, and foot) are found to be covariant along an attractor planar. This planar covariation law has been observed in human running (Hicheur et al., 2006), hopping (Ivanenko et al., 2007), crawling (MacLellan et al., 2017), and various walking tasks, such as level walking (Borghese et al., 1996; Bianchi et al., 1998; Lacquaniti et al., 1999; Dominici et al., 2011; Catavitello et al., 2018; Gueugnon et al., 2019), walking on slopes (Noble and Prentice, 2008; Dewolf et al., 2018), and backward walking (Grasso et al., 1998). Therefore, the synergies can be expected to provide a new, unified, and biologically meaningful framework for describing different types of lower limb movements and examining their similarities. In addition, many studies suggest that the joint synergies play a role in the motor function assessment (e.g., abnormal joint coordination) and treatment planning in rehabilitation (Jarrasse et al., 2014; Ting et al., 2015). Likewise, our previous work finds that the prostheses and exoskeleton developed based on the joint synergies are able to reproduce human-like motor ability (i.e., the reproduction of human-like joint angle trajectories) (Chen et al., 2015; Xiong et al., 2016; Liu et al., 2018). Taken together, it can also be expected that the movement representation based on the synergies will provide new and complementary insights into understanding, classification, and reproduction of the lower limb movements in related fields, compared with traditional gait descriptors.

This paper proposes a measure index of movement similarity through synergy-based movement representation and presents a quantitative categorization for a variety of human lower limb movements. Taking into account the diversity of the human lower limb movements, we collected motion data from the motor tasks which to some extent represent the versatile motor ability of the lower limb in daily living (Kuehne et al., 2011; Mandery et al., 2016). Then, we applied cluster analysis to identify the primary and representative categories underlying the various lower limb movements according to synergy-based movement similarities. Finally, we analyzed the coordination features of the movement categories in the categorization, in order to uncover category-specific control strategies in each category and the set of available and typical synergies used by humans.

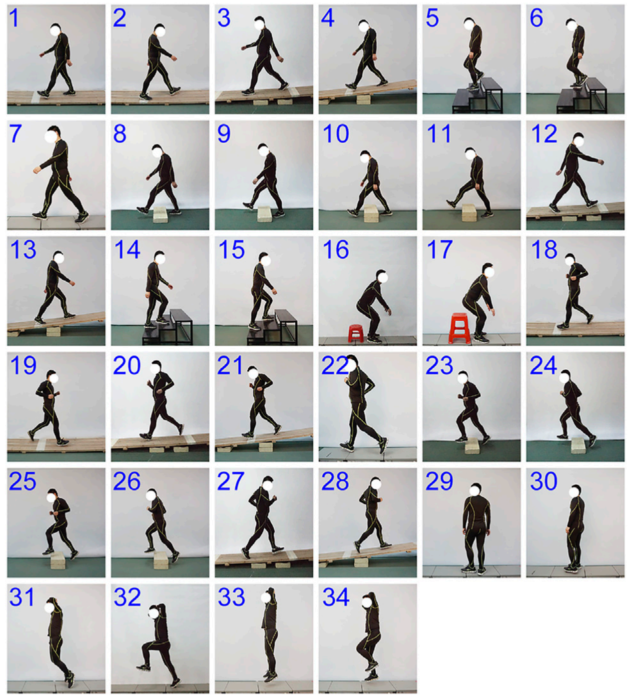

FIGURE 1 | Motor tasks explored in this study. Thirty-four motor tasks are analyzed in this study (Nos. 1–15: walking tasks, Nos. 16 and 17: sitting-down-standing-up tasks, Nos. 18–28: running tasks, Nos. 29 and 30: turning in place tasks, and Nos. 31–34: hopping tasks). Adapted from Huang et al., 2021a.

MATERIALS AND METHODS

Participants

The human lower limb can achieve diverse movements in daily living. To build a comprehensive and representative categorization for the lower limb movements and explore their similarities and differences, a motion dataset from previous work of the authors (Huang et al., 2021a; Huang et al., 2021b) was analyzed in this study. Nine healthy male subjects (age: 23.0 ± 1.0 years; weight: 64.0 ± 6.1 kg; height: 173.1 ± 4.1 cm; mean ± s.d.) participated in the experiment [no differences in the kinematic coordination are found between men and women in the past (Hicheur et al., 2006; Chow and Stokic, 2015)]. The sample size was chosen based on previous studies (St-Onge and Feldman, 2003; Ivanenko et al., 2007; Funato et al., 2010; Catavitello et al., 2018; Dewolf et al., 2018). The experimental protocol was approved by the Chinese Ethics Committee of Registering Clinical Trails. All the subjects provided consent prior to participation.

Experimental Procedure

In this experiment, five basic motor modes which can represent the versatile motor ability of the lower limb were included: walking (Nos. 1–15; **Figure 1**), sitting-down-standing-up (chair height: 30.2 or 42.7 cm; Nos. 16 and 17), running (Nos. 18–28), turning in place (Nos. 29 and 30), and hopping (hopping forward or in place on two legs or only the right leg; Nos. 31–34) (Kuehne et al., 2011; Mandery et al., 2016). Moreover, considering the effect of natural environment constraints on the limb movements, the subjects were asked to walk or run under five typical ground conditions: level ground (7 m walkway; Nos. 7 and 22), cross slopes (incline angle with respect to the level walkway: ± 14.5°; the "+" represented that the left side of the walkway was higher than the right side: Nos. 2 and 19, the "–" represented the opposite case: Nos. 1 and 18), longitudinal slopes (incline angle: ± 2.6° and ±6°; the "+" represented upslope: Nos. 12, 13, 27, and 28, the "–" represented downslope: Nos. 3, 4, 20, and 21), obstacles (width: 30 cm; height: 10 or 20 cm; Nos. 8–11 and Nos. 23–26), and stairs (riser: 15 cm; tread: 30 cm; Nos. 5, 6, 14, and 15). In total, motion data from thirty-four different motor tasks were used in this study. For all the motor tasks, the subjects were asked to choose their preferred speeds and cadences in order to perform these tasks in a natural way. Moreover, all the motor tasks were recorded three times.

The Vicon Motion Capture System (Oxford Metrics, United Kingdom) with 10 cameras was used to record human kinematic data at a sampling frequency of 100 Hz. 20 reflective markers (diameter: 14 mm) were attached to the body landmarks of the lower limbs according to the Plug-in Gait model provided by the Nexus software (Oxford Metrics, United Kingdom). Two additional calibration markers were attached to the left and right medial malleoli during a static trial, which had the subjects stand still. During hopping, the ground reaction forces were recorded by four AMTI force plates (60 cm × 40 cm; sampling frequency: 1,000 Hz; Advanced Mechanical Technology Inc., United States) placed in the middle of the walkway and along the motion direction.

Data Pre-processing

Kinematic data (i.e., hip, knee, and ankle joint angles) were calculated by the Plug-in Gait model after the trajectories of markers were filtered by a Woltring filter with a mean-squared error of 20 mm^2 (Woltring, 1986). The ground reaction forces were low-pass filtered with a fourth-order Butterworth filter (cutoff frequency: 25 Hz).

The foot contact event was determined by the timing when the speed of the heel marker was less than 0.4 m/s during walking and running (Noble and Prentice, 2008) or when the vertical component of the ground reaction forces was greater than 7% of the body weight during hopping (Ivanenko et al., 2007). For walking (except walking up and down stairs), running, and hopping, the motion data over a gait cycle (the time period between two successive foot contacts of the same foot) were retained for each trial. For walking or running over an obstacle, the motion data over a gait cycle that could cover the entire process of stepping over the obstacle were retained. In other words, the motion data between two successive left foot contacts were retained when stepping over the obstacle starting with the right leg, vice versa. For walking up and down stairs, sitting-down-standing-up, and turning in place, the data from the beginning time of the movement to the ending time were retained. After the motion data were selected, the joint angle sequences of each trial were resampled to 200 points using cubic spline interpolation.

Here the coordination patterns among six joint motions of the right lower limb were studied and used to describe the characteristics of the lower limb movements: hip flexion/extension (H f/e), hip adduction/abduction (H a/a), hip rotation (H rot), knee flexion/extension (K f/e), ankle plantarflexion/dorsiflexion (A p/d), and ankle rotation (A rot). Flexion, adduction, internal rotation, and dorsiflexion were defined as positive values in this study. The posture during the static trial (standing still) was set as initial posture so that the mean joint angles during the static trial were subtracted from the joint angle values during each dynamic trial. For each trial, the joint angles of the lower limb were presented as a data matrix $\mathbf{Q} = [\,\mathbf{q}_1 \cdots \mathbf{q}_i \cdots \mathbf{q}_{200}\,]$, $\mathbf{q}_i \in \mathbb{R}^{6\times1}$ represents the posture of the lower limb at the ith moment. To comprehensively characterize the limb movement patterns for a specific motor task, the data from all the three trials were pooled together as a data matrix $\mathbf{Q}_t \in \mathbb{R}^{6\times600}$ for each subject.

Similarity Between Movements

As suggested by the studies in the kinematic synergies, limb joint motions in a motor task can be decomposed into a series of kinematic synergies and reconstructed by their linear combination. The kinematic synergies thus provided a framework for characterizing the various lower limb movements and were used to quantify the similarity between the movements in this study. Following this, we first extracted the kinematic synergies of each of the thirty-four tasks by using principal component analysis on the data matrix $\mathbf{Q}_t$ consistent with previous studies (St-Onge and Feldman, 2003; Ivanenko et al., 2007). In this way, original joint motions could be represented as $\mathbf{q}_i - \bar{\mathbf{q}}_i = \sum_{j=1}^{6} c_{ji}\mathbf{s}_j$. $\bar{\mathbf{q}}_i$ is the average of $\mathbf{q}_i$. $\mathbf{s}_j$ is the jth synergy equal to the eigenvector of the covariance matrix of the joint motions with the jth largest eigenvalue, and the elements of $\mathbf{s}_j$ (weightings) represent the contributions of the joint motions to the synergy [the absolute value of a weighting above 0.25 was defined as indicating significant contribution (Gracia-Ibanez et al., 2020)]. The synergies are ordered according to the variance explained by each synergy from largest to smallest. Thus, the proportion of the total variance explained by the jth synergy is $PVE_j = \lambda_j / \sum_{r=1}^{6} \lambda_r$ (λ_j is the variance explained by the jth synergy and equal to the jth largest eigenvalue of the covariance matrix of the joint motions). c_{ji} (recruitment coefficient of the synergy) represents the contribution of the synergy to the original joint motion patterns at the ith moment.

Then, to measure the similarity between a pair of motor tasks, the similarity between two synergies was first quantified by the absolute value of their scalar product. Two synergies were considered significantly similar if their similarity >0.7 (Tresch et al., 1999; Torres-Oviedo and Ting, 2010). Then, based on the synergy similarities and taking into account the different contribution rates of the synergies, a similarity index (SI) between two motor tasks (e.g., the mth and nth tasks) was defined:

$$SI = \sum_{j=1}^{6} \left(\frac{1}{2} \left(PVE_j^m + PVE_j^n \right) \left| \mathbf{s}_j^m \cdot \mathbf{s}_j^n \right| \right)$$

Obviously, the similarity index ranges from 0 to 1, and a smaller value indicates a higher difference between two tasks.

Identification of Movement Categories

Agglomerative hierarchical clustering method was used to identify the categories of the lower limb movements according to the movement similarities. Before the start of cluster analysis, the similarities were measured among all the tasks and averaged across the subjects. To form the clusters, the similarity between two new clusters at each combination stage was determined by the average linkage algorithm (Johnson and Wichern, 2007).

Hierarchical clustering method always results in a number of possible cluster solutions. In this context, Mojena stopping rule (lower-tail method) was applied to determine the number of clusters in the final solution (Mojena, 1977; Simonsen and Alkjaer, 2012). According to this stopping rule, the optimal cluster solution is the solution corresponding to the first cluster combination stage i, which satisfies the inequality $\alpha_{i+1} < \bar{\alpha} - ks_\alpha$, where α_{i+1} is the fusion level in the stage $i+1$ with $33-i$ clusters (i.e., the similarity determined by the average linkage algorithm); $\bar{\alpha}$ and s_α are the mean and standard deviation of the α distribution, respectively; k is the standard deviate and is set to 1.25 according to the recommendation of a simulation study (Milligan and Cooper, 1985).

Core Synergies of Each Category

After movement clusters were identified, the synergies for a cluster representing the overall coordination characteristics of the cluster (called core synergies of the cluster in the following sections) were extracted from the motion data of all the motor tasks within the cluster. The data from the motor tasks in the cluster were pooled together as an entire data matrix in each subject, and then the synergies for the cluster were extracted. In this stage, to further examine the main differences between clusters, we selected the minimum number of the primary synergies which could capture the main movement variation of the motor tasks in each cluster. To this end, two criterions were used (global and local criterions). First, the main synergies of a cluster could account for more than 90% of the overall movement variance of all the motor tasks in the cluster (Courtine and Schieppati, 2004). Second, the main synergies of a cluster could account for more than 90% of the movement variance of each motor task in the cluster. The stringent local criterion ensured that the characteristics of each task in a cluster could be well described. Following this, the differences between the clusters were examined based on the core synergies using the absolute value of the scalar product of the core synergies.

Statistical Analysis

To examine the subtle differences between two core synergies, the difference in the weighting of a joint motion between two core synergies is further compared using a two-tailed paired t-test. Sample normality was verified using the Lilliefors test. The significance level was set at $\alpha = 0.05$. Similarly, for a specific synergy, the difference in the weighting between two joint motions was also compared. All statistical analyses were performed using MATLAB R2017a (Mathworks, Natick, MA, United States).

RESULTS

In brief, the speeds of all walking tasks (except for walking upstairs and walking downstairs), all running tasks, and all forward hopping tasks ranged from 1.06 ± 0.13 m/s (No. 11) to 1.27 ± 0.13 m/s (No. 4; mean ± s.d. across all the trials performed by all the subjects), from 1.94 ± 0.31 m/s (No. 19) to 2.13 ± 0.25 m/s (No. 22), from 1.46 ± 0.32 m/s (No. 31) to 1.69 ± 0.30 m/s (hopping forward on the right leg; No. 32), respectively. The hopping frequency ranged from 1.40 ± 0.29 Hz (No. 31) to 1.96 ± 0.53 Hz (hoping in place on the right leg; No. 34). The duration of movement was 3.38 ± 0.44 s in walking downstairs, 3.66 ± 0.31 s in walking upstairs, 3.85 ± 0.92 s in sitting-down-standing-up, and 4.76 ± 0.59 s in turning.

Similarities and Categories of the Lower Limb Movements

The similarities among the motor tasks were measured by using the kinematic synergies (**Figure 2**). Three representative clusters or categories (C1–C3) were identified in the diverse lower limb motor tasks, consistent with the visual inspection of the movement similarities. As shown in **Figure 3**, the largest cluster (C1), composed of twenty-eight motor tasks, was formed at a similarity level of 0.76, which included walking, running, and sitting-down-standing-up. The other two small clusters (C2 and C3) were also identified. Hopping tasks (involving hopping forward and hopping in place) and turning were the second (C2) and third (C3) clusters, respectively.

Synergistic Characteristics of the Clusters

The core synergies of a cluster representing the common synergistic characteristics of all the motor tasks in the cluster were further extracted. As the results showed, lower limb joint motions could be reconstructed by combining a small number of core synergies in each cluster (**Figures 4**, **5**). The first three synergies accounted for most of the overall movement variance of all the tasks in each cluster (>90%; 97.34 ± 0.53%, 96.83 ± 0.99%, 95.70 ± 1.11% in C1, C2, and C3, respectively; **Figure 4**). Meanwhile, in each cluster, the limb movement patterns of each task could also be well reconstructed by the first three core synergies (>90%; range: 95.57 ± 1.34% to 99.13 ± 0.51% in C1, 94.93 ± 3.13% to 97.63 ± 1.15% in C2, 94.72 ± 1.69% to 96.41 ± 0.98% in C3; **Figure 5**).

The primary core synergies of the three clusters showed the movement characteristics in each cluster (**Figure 6A**). The first core synergies (CS1) of C1 and C2 were similar (>0.7; similarity = 0.82 ± 0.07; **Figure 6B**) and were characterized by the coordinated movement between hip flexion and knee flexion (or between hip extension and knee extension; average weightings >0.25; **Figure 6A**). However, in C2, ankle plantarflexion/dorsiflexion and rotation also had noticeable weightings in the CS1 (average weighting = 0.58 and 0.30, respectively), different from the CS1 of C1 ($p < 0.001$ and = 0.004, respectively). In C3, it had a special CS1 compared with the other two clusters, which was characterized by the coordinated movement among hip rotation, knee flexion/extension, and ankle rotation.

For the second and third core synergies (CS2 and CS3), the three clusters further showed respective specific synergistic characteristics. The CS2 of C1 was the coordinated movement between hip flexion and knee extension (or between hip extension and knee flexion), and hip flexion/extension had a larger weighting ($p < 0.001$). The CS2 of C2 was mainly

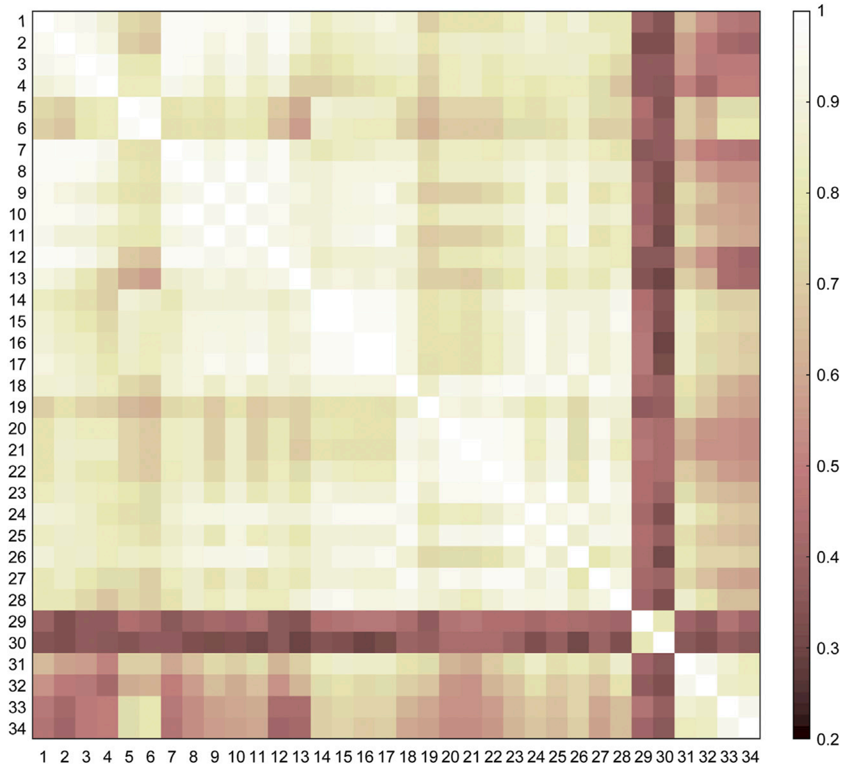

FIGURE 2 | Similarities among the motor tasks. The similarities are the averages across the subjects (n = 9) and are used as the input of cluster analysis.

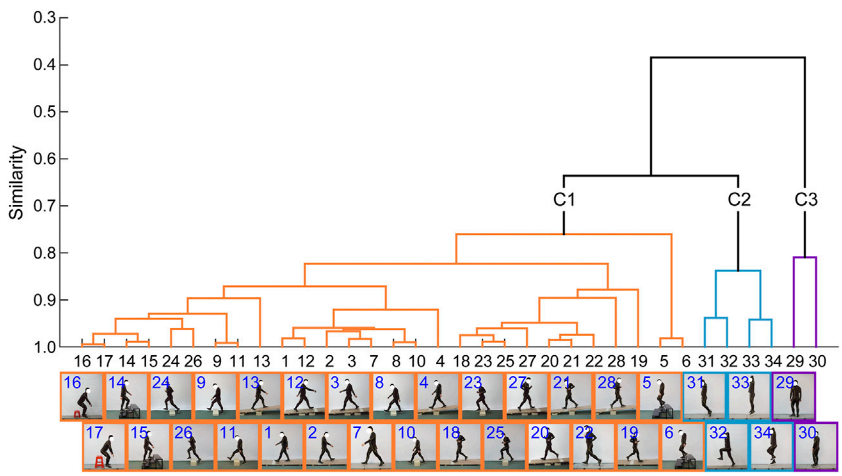

FIGURE 3 | Dendrogram of the lower limb movements. Three clusters (C1–C3) are identified in the various lower limb movements based on the synergistic characteristics of the limb movements.

characterized by the coordinated movement among hip flexion, knee flexion, and ankle plantarflexion. Similar to the CS1, ankle plantarflexion/dorsiflexion had a significant weighting (0.68) in the CS2 of C2, different from the CS2 of C1 ($p < 0.001$). In C3, the CS2 was the coordinated movement among hip flexion, hip internal rotation, and knee flexion, similar to the CS1 of C1 and C2 (similarity = 0.85 ± 0.11 and 0.75 ± 0.11, respectively; **Figure 6B**). Obviously, a primary difference among these similar synergies was the difference in the rankings of their contribution rates in the three clusters (according to the order of the variance explained by the synergies). For the CS3, C1 showed the coordinated movement between hip extension and ankle

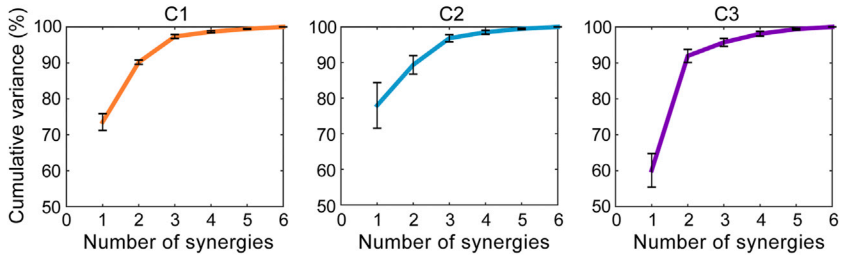

FIGURE 4 | The overall variance of all the tasks in each cluster explained by the core synergies. The core synergies of a cluster represent the common synergistic characteristics of all the motor tasks in the cluster, and are extracted from the data of all the tasks belonging to the cluster. The lines and error bars indicate the means and standard deviations of the cumulative percentage of the overall movement variance explained by the synergies across the subjects (n = 9), respectively.

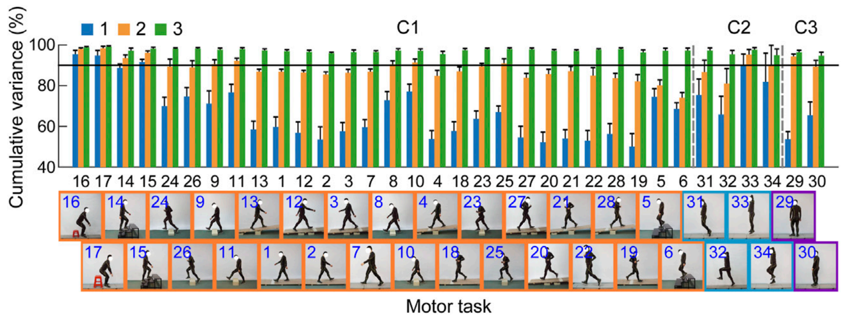

FIGURE 5 | Movement reconstruction of each task by the combination of the core synergies in the clusters (C1–C3). The bar graph depicts the percentage of the total joint motion variance of each task (means and standard deviations across the subjects, n = 9) explained by the first (blue), the first two (orange), and the first three (green) core synergies in the three clusters. The reconstruction quality is considered good if the variance explained >90% (black horizontal line).

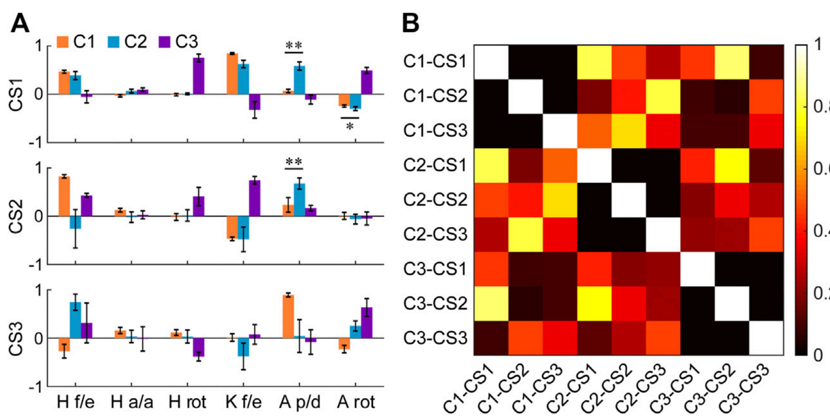

FIGURE 6 | (A) Core synergies of the three clusters (C1–C3). The bars and error bars indicate the means and standard deviations across the subjects (n = 9), respectively. Before averaging, the direction of the core synergies in a few subjects is adjusted (i.e., reversed) when these synergies are not consistent with corresponding reference synergies in a reference subject (i.e., when the scalar product between the synergy needing to be adjusted and the reference synergy is less than zero). Flexion, adduction, internal rotation, and dorsiflexion are defined as positive values. *p < 0.01, **p < 0.001 (two-tailed paired t-test). Abbreviations: CS1: the first core synergy; CS2: the second core synergy; CS3: the third core synergy; H f/e: hip flexion/extension; H a/a: hip adduction/abduction; H rot: hip rotation; K f/e: knee flexion/extension; A p/d: ankle plantarflexion/dorsiflexion; A rot: ankle rotation. **(B)** Similarity matrix of these core synergies (means across the subjects, n = 9). The similarity between two synergies is quantified by the absolute value of their scalar product. Two synergies are considered significantly similar if their similarity >0.7. Each of the abbreviations (from C1-CS1 to C3-CS3) represents a core synergy of a cluster. For instance, C1-CS1 represents the first core synergy of the cluster 1.

dorsiflexion, and ankle plantarflexion/dorsiflexion had a larger weighting ($p < 0.001$). The CS3 of C2 was the coordinated movement among hip flexion, knee extension, and ankle internal rotation, which was different from the CS3 of C1 and C3 (similarity = 0.35 ± 0.21 and 0.46 ± 0.26, respectively; **Figure 6B**), but similar to the CS2 of C1 (similarity = 0.80 ± 0.13). In C3, the CS3 was the coordinated movement among hip flexion, hip external rotation, and ankle internal rotation, which was also different from the other clusters.

DISCUSSION

In this study, we investigated the quantitative similarity measure and hierarchical categorization of the diverse lower limb movements. Different types of lower limb movements (including cyclical and non-cyclical ones) were well described by a unified movement descriptor, namely, the kinematic synergies, which represent kinematic control strategy in the execution of the limb movements. Based on synergistic characteristics, the similarities among the lower limb movements were quantitatively measured, and three primary homogeneous clusters (C1–C3) were identified within the diverse lower limb movements. The existence of the clusters suggests a numerical categorization model for the human lower limb movements. To our knowledge, this categorization is also the first quantitative categorization for a variety of human lower limb movements to date.

Our categorization establishes a hierarchical structure for the many lower limb movements and divides them into three representative sub-motion categories. By this division, our results provide new insights into the formation mechanisms of the lower limb movements in physiology. The first category (C1), as the largest one, is composed of walking and running under various ground conditions and sitting-down-standing-up. The existence of C1 suggests that similar control strategies are adopted by humans when they perform these walking, running, sitting-standing tasks. This finding supports that humans simplify the generation of a variety of lower limb movements (including diverse gait modes and interaction styles with the environment) by reusing the same basic motor synergies, without the need to develop new synergies *de novo* for each movement. Through this conservation of the kinematic synergies, the seemingly daunting task of achieving the many movements with diverse motor task-related and environmental constraints can be completed in an effective and simple manner. Likewise, the control of motor tasks is also simplified by employing similar synergies in each of the other two categories (C2 and C3). On the other hand, the existence of the three different categories also suggests the flexibility and plasticity of the human motor system. In order to achieve some category-specific behavioral goals or learn several novel skills, humans can also develop new motor synergies. Overall, these findings suggest the coexistence of the conservation and augmentation of the motor synergies underlying the generation of the lower limb movements.

The limb movement patterns of the motor tasks in each category can be effectively generated by the combination of three core synergies. In C1, the coordination of hip and knee flexion/extension plays an important role in the generation of the limb movements, as indicated by the coordinated movements between hip flexion and knee flexion (or between hip extension and knee extension) in its CS1 and between hip flexion and knee extension (or between hip extension and knee flexion) in its CS2. Moreover, the CS3 with the maximum weighting in ankle plantarflexion/dorsiflexion implies that the control of the ankle joint motion is also critical in C1, consistent with the notion that limb endpoint control requires accurate control of the ankle joint motion in human locomotion (Ivanenko et al., 2007). For C2, similar to C1, the coordination of hip and knee flexion/extension also contributes to the formation of the limb movement patterns, as indicated by the synergistic characteristics in the CS1–CS3 of C2. However, different from C1, the main coordination manners adopted by C2 is the coordination of ankle plantarflexion/dorsiflexion with hip and knee flexion/extension. Ankle plantarflexion/dorsiflexion has greater weightings in the CS1 and CS2 of C2 than in the CS1 and CS2 of C1 (**Figure 6A**). In particular, the coordination among ankle dorsiflexion, hip flexion, and knee flexion (or among ankle plantarflexion, hip extension, and knee extension; the CS1 of C2) is in line with the power transfer mechanism of biarticular muscles among the hip, knee, and ankle joints in hopping (Junius et al., 2017; Schumacher et al., 2020). Through the coordination of the joint motions and the action of biarticular muscles (close to isometric contraction, that is, almost zero contraction velocity), the power can be effectively transported from the hip and knee joints to the ankle joint (or from the ankle joint to the hip and knee joints). In this way, the power demand on the ankle joint that

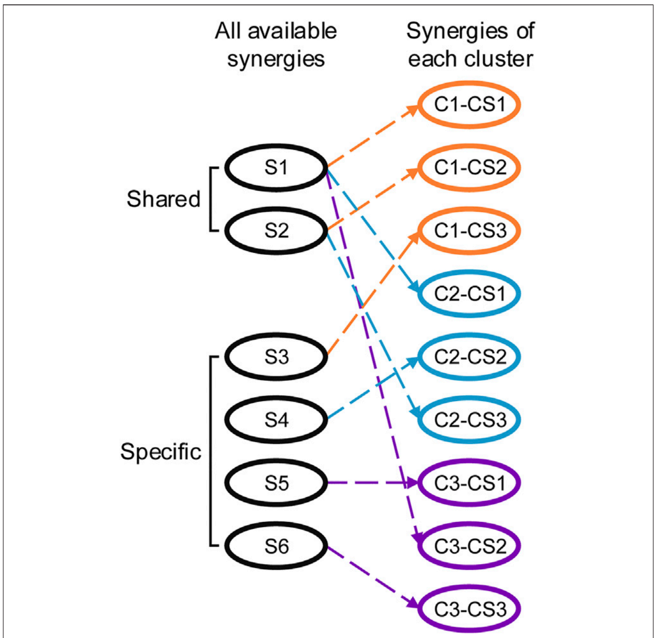

FIGURE 7 | Typical and available synergies employed by humans to achieve the various behavioral goals of the clusters. Shared and specific synergies exist in the three clusters and are used to meet cluster-independent and cluster-dependent behavioral demands, respectively.

may exceed the capability of ankle joint muscles can be met by the power from the hip and knee joints in hopping. Likewise, this power transfer may also exist between the hip and knee joints *via* their coordination in walking and running tasks (i.e., C1) (Neumann, 2010; Junius et al., 2017). For C3, the existence of the category composed of only turning tasks is consistent with the specific behavioral goal of turning. Different from the other lower limb movements included in C1 and C2 with the aim to push the body forward, upward, or downward, the goal of turning is to rotate the whole body (Ivanenko et al., 2007; Akiyama et al., 2018). This difference is also well characterized by the unique synergistic characteristics of C3 (the coordinated movements between hip and ankle rotations). Taken together, the three categories employ their respective unique synergies.

Besides the uniqueness of each category, more interestingly, high similarities are also found among some of the synergies of the three categories. In total, there may be a total of six synergies available for the three categories (**Figure 7**). Two of the six synergies are shared across the categories, and each of the other four synergies is exclusive to a category. Meanwhile, as indicated by our results, the shared synergies also show subtle but significant changes in the weightings of a few joint motions and changes in importance in the three categories. For instance, the second shared synergy (S2) is the second synergy in C1 (C1-CS2), but the third synergy in C2 (C2-CS3). Overall, these findings further suggest that humans can achieve various behavioral goals rapidly and effectively by retaining, fine-tuning, and augmenting the collections of pre-existing motor synergies.

Our categorization also provides inspiration for the studies related to the lower limb movements, such as the motor function assessment and treatment planning in rehabilitation and the development of artificial limbs in robotics (Papageorgiou et al., 2019; Stival et al., 2019). In these studies, the complex question of learning the characteristics of the various lower limb movements can be solved by dividing the many movements into three small, homogeneous, and manageable sub-motion categories. The motor behaviors within one of the three categories which have shared movement strategies can be modeled and analyzed in the same manner. On the basis of the characteristics of each category, customized and standardized rehabilitation programs can be formulated for each of the three categories. The motor function of the lower limb can also be effectively assessed in the process of rehabilitation treatments. Similarly, in robotics, an effective method that can be used to improve the functionality of the artificial limbs reproducing the lower limb movements will be to develop specific mechanical systems for each category or modular/dynamic control systems based on the movement categories. Meanwhile, the core synergies of each category also provide references for the comparison between the human and artificial limbs, which can further accelerate the development of better artificial limbs. In addition, the existence of the three different categories also suggests the strategy of prioritizing part of the categories according to practical demands in rehabilitation and robotics (e.g., feasibility of motor recovery or functional requirements of the artificial limbs).

As a descriptor to characterize the lower limb movements, the kinematic synergies represent the coordination strategy in the movement process and provide a basis for measuring the similarities among different types of lower limb movements in this study. Based on this, a categorization composed of three distinct movement categories is successfully built, and task-independent and task-dependent synergies are also revealed in human locomotion. In fact, in addition to the lower limb movements, kinematic coordination has also been found in the other limb movements, such as hand grasps (Xiong et al., 2016; Jarque-Bou et al., 2019) and upper limb movements (Schuetz and Schack, 2013; Liu et al., 2018). Consequently, this synergy-based movement representation has the potential to be used to quantify the similarity of the other limb movements. Moreover, synergies have also been observed at kinetic or muscular levels (Giszter, 2015; Scano et al., 2017). This means that our measure method of movement similarity can also be extended by taking into account the kinetic and muscle synergies in the future, which will provide more detailed and complementary information regarding the generation of the limb movements.

There are some limitations to the study. First, to identify the sub-motion categories underlying the diverse lower limb movements, here we selected thirty-four typical motor tasks, which to some extent represent the versatile motor ability of the lower limb (Kuehne et al., 2011; Mandery et al., 2016). However, it is well known that humans can move in an infinite number of ways in daily living. In this case, while it can be expected that our methodology will also be able to provide beneficial guidance for the characterization of the motor tasks that are not explored in this study, further analyses need to be performed in the future. Likewise, in practical applications, researchers may also pay attention to only part of the motor tasks we have studied. For these tasks (e.g., only walking and running), our methodology must be adapted in order to obtain a partial categorization, and subtler movement characteristics may be further uncovered. For example, the dendrogram in **Figure 3** shows that walking downstairs may require somewhat different kinematic synergies from the other walking tasks and trends to form a single category. Second, the number of participants included in this study was small ($n = 9$). In the future, the sample size should be enlarged for further verification of our methodology. Third, only healthy adults were considered in this study. Future work is necessary to evaluate the efficacy and versatility of our methodology in characterizing the other human gaits (including gaits of children or older adults or diverse pathological gaits). Fourth, here we only analyzed the joint kinematics without considering the joint kinetics or muscle activities. As mentioned above, further studies extending our methodology by considering the kinetic and muscle synergies are necessary, which can provide new insights into the formation mechanisms underlying the lower limb movements.

CONCLUSION

This study proposes a general framework for measuring the similarities among the limb movements based on the kinematic synergies and establishes a quantitative and hierarchical categorization for the lower limb movements. Three main categories are identified. In each category, the motor tasks can be well reconstructed by combining three core synergies, and shared synergies are also found across the three different categories. The coexistence of synergies shared across the movements and categories and synergies for specific categories thus suggests that there exists an effective strategy for humans to simplify the formation of the various lower limb movements by retaining, fine-tuning, and augmenting initial collections of the kinematic synergies. Besides providing inspiration for understanding human movements, the categorization consisting of manageable and homogeneous categories can also be expected to facilitate the motor function assessment and treatment planning in rehabilitation and the development of better artificial limbs in robotics, which deserves to be investigated in the future. Moreover, our proposed approach also provides a means to quantify the degree of similarity and build a hierarchical description for the other human limb movements, even the movements of other animals.

DATA AVAILABILITY STATEMENT

A publicly available dataset was analyzed in this study. This data can be found here: Dryad Digital Repository, https://doi.org/10.5061/dryad.wdbrv15n9.

ETHICS STATEMENT

The study involving human participants was reviewed and approved by the Chinese Ethics Committee of Registering Clinical Trails. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CX conceived and directed the study. BH and WC designed the experiment. BH collected and analyzed the data. BH, WC, JL, LC, and CX interpreted the results and wrote the manuscript. All authors approved the submitted version.

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Show Me, Tell Me: An Investigation Into Learning Processes Within Skateboarding as an Informal Coaching Environment

Rosie Collins[1,2]*, *Dave Collins*[2,3] *and Howie J. Carson*[3]

[1] *Department of Sport, Health Sciences and Social Work, Oxford Brookes University, Oxford, United Kingdom,* [2] *Grey Matters Performance Ltd., London, United Kingdom,* [3] *Human Performance Science Research Group, Institute for Sport, Physical Education and Health Sciences, The University of Edinburgh, Edinburgh, United Kingdom*

Coach education is a learner-centred process, which often fails to consider the preferences of the consumer. Historically, research into performers' experiences of coaching have been influenced by the social constructivism of learning: in short, an expressed preference for what the performer has experienced as determined by their coach, rather than their own personal preferences. Therefore, this research used skateboarding as a natural laboratory in order to explore the current practices and preferences of performers in a coach-free environment. Ninety-one skateboarders from parks in the United Kingdom and New Zealand offered information relating to their current learning practices, how they learnt about learning, and how the top-level performers in their environment were differentiated. Findings suggest that a number of learning tools are used by performers, which are closely aligned with a more traditional, cognitive view of coaching (e.g., demonstration, drills, and error usage). Results also suggest that performers deployed a number of cognitive skills (e.g., imagery, analogy, and understanding) to enhance storage of a movement as an internal representation. Finally, in the absence of formal coaching, performers use their knowledge of learning to appoint informal leaders. Implications for practice are discussed.

Keywords: cognitive psychology, demonstration, imagery, psychological skills, understanding, motor skills

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Australian Catholic University,
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Russell Martindale,
Edinburgh Napier University,
United Kingdom
Michel Milistetd,
Federal University of Santa Catarina,
Brazil

***Correspondence:**
Rosie Collins
collins@brookes.ac.uk

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INTRODUCTION

For decades, sport researchers have focussed on understanding the processes, tools and frameworks for, and of, optimum coaching practices (Côté and Gilbert, 2009). This information has then been disseminated through a wealth of channels, from the formal and peer-reviewed, to the informal and personally speculative (cf. Stoszkowski et al., 2020). Consequently, what we would typically call "coach education," or coach development, has become a serious business. The evolution of coach development has seen coaches at the centre of the process, sometimes seeking to understand the nature of preferred support (i.e., informal or formal; Mallett et al., 2009), sometimes considering the evaluation of coaches (i.e., coach behaviours; Cushion, 2010) and sometimes even promoting the switch toward a *learner*-centred process (Paquette and Trudel, 2018). Indeed, recent research has started to consider what coaches need from the consumer (athlete; e.g., Becker, 2009), why athletes follow coaches (e.g., Rylander, 2015) and who coach development policy should be cascaded to (Dempsey et al., 2021). From this research, it is clear that coach education has proven to be impactful, influencing both the initial and continual training of professional coaches.

Whilst this investment has undoubtedly improved the provision and services of coaching, it does seem as though there is something lacking. Similarly to the situation some time ago within the education sector (Trigwell and Prosser, 1991), there has been considerably less research to address what the consumers of the coaching think constitutes the highest quality of learning experience. Indeed, the notable swing in education has seen a movement away from exploring the quality of *teaching*, instead to look at the quality of *learning* (Plowright, 2007). For example, common practice is to speak with, or canvas, pupils to explore their experiences and understand their preferences for learning (Hobson and Talbot, 2001). Indeed, this has even resulted in the development of a particular measuring tool (Evaluation of Teaching Competencies Scale; Catano and Harvey, 2011) that is built on consumer perceptions. Inspired by this advancement through a change in perspective, sport coaching may equally benefit by employing such an approach.

However, when asking athletes directly about what they prefer, a key problem relates to their socially constructed knowledge of coaching (Potrac et al., 2000; Shoukry and Cox, 2018). For example, if a performer likes the coach, it is probable that they will adhere to and endorse the methods they use. Conversely, if they dislike the coach, they will not respond so positively. Whilst this might be indicative of a thought through and considered reflection on the coaching process, it might be confounded by other much less "rationalised" perspectives. Moreover, it has been suggested that tradition and historical precedence often guide coaching practice (Williams and Hodges, 2005), which might act to limit coach education's ability to innovate based on a performer's needs and the learning context. In order to overcome this problem, research should look to explore the "bottom-up" preferences and behaviours of performers who have been conspicuously absent from these influences (i.e., a coach free environment) in order to verify what seems to be valued, enacted and advantageous.

Historically known for its accessibility as a sport (i.e., low equipment costs and few precursors required to be successful; SkateboardGB, 2020), skateboarding has recently become considerably more mainstream since its inclusion in the Tokyo 2020 Olympics. Skateboarding now joins the likes of freeskiing and freestyle snowboarding as a young sport in the mainstream, something which is certainly not without its challenges. Willmott and Collins (2017) and Collins et al. (2018) highlight these difficulties by suggesting that many coaches within the environment, formal or otherwise, are often left floundering, either copying the pathway of successful athletes in other sports or "overly influenced by the waves of new but unspecific sport science support now available" (Willmott and Collins, 2017, p. 2). Of most relevance, however, is that as with many other action sports, skateboarding presently remains largely coach-free (see Ellmer et al., 2020). In other words, training practices within the sport are most likely to exist because they are shared amongst, and learnt from, peers, or because it simply works for an individual. Notably, not because a coach said they should. Therefore, skateboarding, when examined outside of (new) competitive contexts (cf. Collins and Carson, 2021), offers an opportunity to explore a relatively "pure" learner-governed perspective on what works, albeit that this opportunity must be exploited quickly before the sport moves to the mainstream of coach-led activity.

To exploit this opportunity, this study aimed to explore the self-reported nature of learning and development in an informally coached, or indeed coaching-free environment, to better understand which tools were used, how performers developed and how these tools were deployed. Furthermore, if there was a difference between the top performers' (i.e., "top-enders") approaches compared with the developmental or simply "less proficient" performers. In exploring this, we aimed to obtain information pertaining to the focus of the performers during skill development and execution. Therefore, the objectives were as follows:

1. To explore how skateboarders learn new skills in the absence of formal coaching.
2. To establish how, and from where, skateboarders gain coaching insights.
3. To identify how and/or why "top-enders" were more successful performers.

MATERIALS AND METHODS

Participants

Following approval from the researchers' University Ethics Committee at University of Central Lancashire, where DC and RC were based before the beginning of the study, 102 performers were approached across seven skate parks in the United Kingdom and New Zealand. All appeared to fit the age criteria (16 years or older) and were confirmed by a gatekeeper (more details on the gatekeepers role are outlined below) for that site as a regular attendee (i.e., recognised by the gatekeeper as a frequent skateboarding participant, consistently attending each week). Of these, eight were younger than the target age and three declined to participate, resulting in a final sample size of 91 participants (9 "top-enders", 82 developmental; 82 males, 9 females; M_{age} = 17.3 years, SD = 1.1; $M_{years\ training}$ = 4.2 years, SD = 1.8; $M_{park\ visits}$ = 3.1/week, SD = 1.2, $M_{session\ duration}$ = 78 min, SD = 18). This "by eye then check" sampling method (Gyure et al., 2014) resulted in approaches to around 65% of those in the park at the time of visit. In other words, even though the age stipulation prevented the research team from questioning approximately one third of the available participants, the sample still generated representative results. This perception was confirmed by the gatekeepers as "external verifiers." Using the dimensions proposed by Collins and Carson (2021), participation at each site was in a manufactured environment and regulated as a community of practice. All participants gave their informed consent to partake in the research.

Instrumentation

As indicated earlier, the scope of enquiry was considerably broad, addressing the tasks of skill acquisition, refinement and practice. As such, it was imperative to maximise the impact for this specific group of performers, whilst also offering a useful perspective for the more general coach development literature. Accordingly, major issues which could be addressed effectively within the constraints of the study environment were considered first. Purposefully, we sought to collect these data atheoretically in an attempt to maintain a lack of bias toward any literature-informed theory or framework of formalised coaching. This led to the development of a draft set of questions that was initially piloted with six performers from two skate parks not involved in the main study. A process of cognitive interviewing (a tool to administer open-ended questions in an effort to review question understanding and nature of response, e.g., "did you find any of the questions difficult to understand?", "what do you think this question refers to?", "could any of the questions be rephrased to help you understand them more?"; Beatty and Willis, 2007) followed this pilot process and resulted in three changes that offered greater clarity against issues raised. The final interview tool was comprised of:

1. Consider difficult tricks or sequences you learnt recently or are learning.
    a. How are you learning/did you learn them?
    b. What did you use to help?
    c. What else would have helped you?
    d. What do you do if/when you make a mistake?
2. Where have you picked up ideas on how to get better?
3. Who is/are the best performers in this park? (used to identify the "top-end" performers whom were approached after being identified).

Based on this line of questioning, participants were free to interpret and express their learning experiences as relevant to them and unguided toward any theoretical position.

Procedure

A member of the research team originally approached the management of each skate park to seek permission to undertake this research and approach performers. This approach was made in association with a park-specific and previously identified gatekeeper who had been recruited through personal contact. Gatekeepers were uniformly over 21 years old and experienced riders themselves. Most importantly, they were regular attendees at that particular skate park and were well known to the other performers at that venue.

Following approval from skate park management, one member of the research team (two researchers collected data across the countries) attended the park with the gatekeeper, approaching individuals together, to invite them to take part. Individuals were only approached if they were recognised by the respective gatekeeper as being regulars at that particular park. A key and early part of this approach was an explanation of our purposes, provision by the researcher of photo identification and an explanation as to how the study would work from an ethical perspective. In brief, participants were guaranteed anonymity. Indeed, the research team deliberately did not record their names, but only took age and participation data for the purposes of describing the sample. Each participant was assigned a number at this stage to enable future withdrawal upon request.

Since the study aimed to obtain participants' views on the topics addressed in the questions, no *post hoc* interpretative analysis was intended. Rather, accuracy of recording and individually confirmed viewpoints were sought at the time of interviewing. Accordingly, questions were asked by the investigator whenever the participant's statement was unclear or could be misconstrued. Importantly, however, probes were used sparingly to avoid any tendency to lead the participant. For example, to avoid leading participants into giving the researchers the answer they thought we might be after, and any potential researcher-bias based on formal coaching literature. Probes were only utilised to seek clarity, such as when using sport-specific language, or to check the researchers' understanding of the participants' statements. This approach resulted in a conversation, with the interviewer reporting back what had been heard and asking for the participant's confirmation whenever things were not clear. This process received further clarification by the gatekeeper, especially when technical skateboarding terms were used. This process was our best attempt to avoid any issues caused by the lack of member reflections when addressing the trustworthiness of our research (see section "Trustworthiness" below for additional details and steps taken).

Interviews lasted between 22 and 40 min (M = 33.3 min, SD = 6.9), with a roughly equal split of participants contributing across the four data collection sites. At each site, every individual identified by the gatekeeper as meeting the participant criteria was invited to participate. Upon completion of the fourth and final site visit, data processing commenced with the view to establish levels of data saturation.

On completion of each interview, the researcher handed the participant an information sheet, with their participant number noted. This provided written details which had already been explained to the participant, inviting them to reflect on the participatory conditions themselves and, if under 18 years old, check these with their parents or guardians at the earliest opportunity. On this sheet, the lead researcher invited phone or email contact if either participant or parent/guardian did not wish them or their data to be included in the study. Importantly, no such calls were received although we did receive 10 inquiries about the study with interest in the results. Importantly, this information sheet also provided details of the University complaints procedure in case parents/guardians or participants had concerns about the process. Once again, no such calls were received.

Data Analysis

To some extent, these data can be considered as inductively analysed because the researchers held no expectations or structures (skateboarding specific knowledge) prior to the investigation. Against the first, and arguably overarching objective, a more thorough exploration was warranted to tease out any nuances across participant responses. Reflecting qualitative innovations by Braun et al. (2016) and Braun and Clarke (2019), raw data codes were compiled in order to identify Central Organising Concepts (COCs; Braun et al., 2018). This was a comparatively straightforward process since responses had already been clarified/confirmed by participants. Reflecting the pragmatic nature of this research, utilising reflexive thematic analysis allowed the data analysis process to accurately reflect the participants' experiences and preferences for learning in an inductive manner (Braun et al., 2018), as the typical "checking" processes had been completed at the point of data collection (Denscombe, 2007). Due to the simplistic nature of Objective 2, the findings were reported by grouping the same responses from participants, as verified at the time of interviewing.

Moving forward, having established the key data themes, Objective 3 was answered by comparing data which were already analysed between "top-enders" and the remaining participants, using a more deductive (against the established COCs) thematic discourse analysis (Clarke and Braun, 2014). This objective was an extension of the first (i.e., how might "top-enders" differ in learning), therefore, pragmatically this more fluid and dynamic analysis tool was deemed pragmatically appropriate.

Trustworthiness

In addition to the steps outlined above, we sought to ensure maximal trustworthiness of these data in order to support the pragmatic philosophy underpinning this research. We were especially aware that researchers are not able to extract themselves from their own experiences, and therefore biases (Denzin, 2017). Accordingly, interactions were almost entirely participant driven, with the investigator completing "real-time" member reflection by reporting back responses to each participant. As stated above, the comparative simplicity and straightforward nature of these responses were major factors in deciding on this approach.

Responses were also subjected to two "external" checks. Firstly, a digest of the data was shared with each gatekeeper, asking for their opinions as to the veracity of the data. In short, whether anything that they had heard, or that the researchers reported back to them, sounded odd or out of the ordinary. No such opinions were expressed, with gatekeepers "endorsing" the results as representative of their own experiences, knowledge and actions in skateboarding. As a further and final check, the results were shared with two experienced international action sport coaches (one from the United Kingdom and one from New Zealand, both with over 15 years' experience as full time coaches) who were asked the same questions; that is, whether anything struck them as surprising or different to their experience, together with their observations of the messages within the data. Although not skateboarding coaches (one was a free skier whilst the other coached snowboarding), both were very in touch with the action sports scene and familiar with skateboarding through their work with their own performers. Once again, the results were endorsed as presenting a true and accurate picture of the milieu by both subject matter experts (SMEs). One of these SMEs, Sean Thompson, the Head Snowboard Coach for New Zealand, offered the following insight:

> Being a lifelong action sports enthusiast, I have dedicated decades of time both learning and coaching board sports such as surfing, skateboarding and snowboarding. My current role as the Olympic Slopestyle and Big Air snowboard coach puts me in the frontline of working closely with an array of athletes in a similar demographic to that studied in this paper. All findings and correspondence from the riders within the paper are what I would expect to be the norm from that age group in that sport.

Both coaches were happy for their names to be reported. The other was Pat Sharples, Head Coach of Snowsports GB.

Finally, the data analysis approach was informed by the research team's applied experiences, one of which was not involved in the data collection process (37, 13, and 8 years' experience in sport coaching, supporting performers up to international level). In contrast, and positively, the lead researcher had little understanding of skateboarding participation, without explicit expertise which could bias their view. The team also brought considerable literature-derived knowledge or theoretical knowingness (Braun et al., 2016). Notably, this allowed the data analysis process to accurately reflect the participants' experiences and therefore provide practical information surrounding a practical problem (Denscombe, 2007), whilst also offering sufficient background to understand and interpret their perspectives (which, again, were confirmed through the "checking" process at the point of interview). As well as the various checks reported so far, the third researcher with expertise in coaching theory and practice acted as a critical friend. Specifically, this knowingness reflected the mechanistic principles outlined by a variety of theoretical approaches. In this way, data were meaningfully analysed through reflexive, transparent engagement, thus working toward a "richer more nuanced reading of the data" (Braun and Clarke, 2019, p. 594).

RESULTS AND BRIEF DISCUSSION

Results with brief discussion points are presented in three sections to reflect the research objectives. Against the first research objective, a summary table is provided to offer an overview of data (a percentage respondent score is included to illustrate how often the COCs were mentioned to represent commonality, as opposed to signifying their importance; Taylor et al., 2017) followed by an exploration of the COCs (in some cases, for ease, presented together). Results for Objective 2 are reported as an overview of participant responses. Finally, Objective 3 is presented as a derivative of the first two objectives, by highlighting the distinguishing characteristics of "top-enders."

Objective 1: How They Learnt

Reported learning methods are summarised in **Table 1**, with exemplar quotes used to provide detail for each theme.

Analogy, Feel, and Internal Representations

When practicing or learning skateboarding skills, participants reported a high prevalence of explicit and analogy learning strategies. Specifically, these explicit and analogy strategies are conscious patterns of thought, or foci of attention, that help to generate the movement mechanics to be performed (Poolton and Zachry, 2007). Analogies were reported particularly often,

TABLE 1 | Participants reported use of learning tools.

Central organising concept	Reported by	Exemplar quotes
Analogy, feel and internal representations	44 (48%)	To help me get the rhythm I'll often see a picture in my head that makes me feel like I want it to look. For example, lots of the time. I'm seeing myself surfing a wave. I might see someone interviewed on [skateboarding website]. He will be talking about something else he's done that helps him get the move right. "Whipping cream" when riding a bowl is one that's helped me a lot.
Attention	78 (85%)	Lots of time I'll pay attention to what I look like. After all that's a big motivation for being here. Every so often I'll work on what the move feels like. I'll stay inside my head and get the feel before I do it.
Imagery/Mental practice	85 (93%)	I'll lie awake in bed running through a trick – what it will feel like and, to be honest, how good I'll look! When I get the chance to watch someone doing a target trick, I'll watch then try and feel how it would be for me. I'll do that loads of times till I think I've got the idea.
Demonstration	80 (88%)	I always take the chance to watch someone perform. I learn so much from it. . . I look' specially when the good guys are riding, I'll take a sneaky peek!
Explanation	78 (85%)	I find it really useful to talk things through with other riders. They often highlight things I haven't thought of. I love it when someone agrees to talk me through how they're doing something.
Error usage	45 (49%)	I'll watch a run several times. I want to see what I'm doing wrong so I can correct it. I like to talk over mistakes with my mates, I want to see what they think I should do.
Practice	90 (99%)	This is all about practice. . .repetitions till I look smooth and effortless. My aim in practice is to look consistent and smooth. . .I want to flow.
Planning and preparation	80 (88%)	I usually think about what I will do on the way to the park. . .set myself some challenges or whether I'll just ride depending on how I feel. I take a competition schedule and work out what I need, when I need it.

interestingly in the form of pictures and thoughts of surfing. As expressed by this rider, "I love to ride round a bowl and picture myself cutting up and down a wave," or from this experienced rider: "to keep my balance I will often imagine a piece of string pulling up from the top of my head." As such, reported thoughts about movement patterns were directly and positively related to the completion of the task, skill or "trick."

Another interesting finding was the deep understanding of tricks or sequences which many participants found really important for their learning, such as "I don't only want to know what it looks like or what it feels like when I do it well. I want to understand how it works from a kick flick upward." Another more experienced 19 year-old rider explained:

> I guess as the older dude around the park I get a lot of young guys asking my advice. I always want to make suggestions to them that develop their understanding of what they're trying to achieve. I use words, symbols, stories [probing suggested this to be metaphors] or pictures to do this.

Accordingly, participants reported the development of an internal, or mental, representation as defined by hierarchically stored movement-relevant knowledge (Schack and Mechsner, 2006) to support their own learning and that of others. Notably, however, these were often driven by a mixture of internal and external constructs, for example: "I really want to know how a sequence will run before I do it. I'll store and practice that usually as a combination. . . imagining it and what it looked like against the 'list' of moves," "I run through a list of moves in my head and the rhythm. . .often I'll get the rhythm of the moves from a favourite piece of music. You mentioned 'Eat, Sleep, Rave, Repeat.' I use it!", or from this 17-year-old: "I've actually set up a run list at home with video cuts for each move. I've been using that to put together an ideal run or sequence. . .putting things together as I can physically do them."

Attention and Imagery/Mental Practice

Interestingly, there were clearly a number of participants who thought about what they attended to, when and why. External focus was commonly used (often facilitated by use of video) for example, "I'm worried about what I look like doing the run, how smooth it looks and what impression it's going to make." There were notable situations, however, in which participants also reported using an internal focus. "As I'm watching someone do a trick, I'm trying to imagine how that will feel. . .I watch out, then think in." Or this 18-year-old: "I often run through the rhythm and feel of the sequence just before I do it to get me ready."

Unsurprisingly, use of imagery was a prevalent tool used by participants. Around 90% of participants reported using imagery in some shape or form, although two broad categories were apparent (Cumming and Williams, 2013). Firstly, mental run-throughs at home or away from the park venue. Content seemed to include elements of mental rehearsal and "ideal performance" motivation; sometimes in combination. For example, one participant recalled:

> When I first went for a "Crooked Grind" [a slide along a rail on the front of the board] I fell and broke my nose. After that, I would watch a demo video on [website], seeing myself do the trick, then feeling how it would be if that were me.

The second category related to imagery *at* the park, which was reported as both preparatory (mental rehearsal) and as a combination with action observation (see section "Demonstrations and Explanations"). For example, as this participant reported, "So when I was working on improving my Nollie Flip [jump up as board rotates under you then land] I would watch a video on my phone, then run through how it would feel. So watch, feel, then do." This combination of mental run-throughs in combination with some form of "instruction" (either watching video, receiving instruction or watching someone else) was extremely common.

Interestingly there was some evidence for a switching of attention, often in a "whole-part-whole" approach. For example, "I always find it important to think through the whole run and what it looks like before going inside my head to check the feel of the difficult dismount or bit in the middle." Or this 16-year-old: "what we've been talking about, inside my head or watching myself or focussing on what the thing will look like; I use them all. . .it depends!" In summary, a mix of external and internal foci were apparent in this sample (Oliver et al., 2021).

Demonstrations and Explanations

Across participants, demonstrations played a big role. Almost all used others as formal (show me how) or informal (covert watching) models. Additionally, although not strictly explanations, verbal input from other riders was extremely common across our sample, for example something Hollett (2019) has termed "vibing," was a common feature. This involved small symbiotic relationships across riders. These "mutual interest groupings" or communities of practice (Culver and Trudel, 2008) then used video and still images, usually from phone cameras or similar, as the basis for after-action debriefs on what had happened and to identify areas for improvement. As one rider put it, "yeah, it's really important to get a perspective from my mate on how I've done," and another, "we'll usually work in the evenings, usually on social media especially at the moment, debrief on progress and set some targets for what I need to change."

Loss of credibility seemed to be the only barrier to using demonstrations as an overt strategy, as explained by this participant: "**** it wouldn't be cool if I was walking round staring at all the other skaters!". Subsequent to watching, either overtly or covertly, participants would try to work out what they would have to do to accomplish what they had seen. In this form, demonstrations were used in a juxtaposed fashion through combinations of imagery and observational learning. Examples from participants include: "I'll pick a star performer and watch how he does a sequence then go and try it myself, trying to reproduce what I saw with what I'll feel," or:

> I'll often ask for advice or if someone minds me hanging with him. Often, I'll approach them and say "hey that was sick. . .how do you do that" and they'll usually show me and offer a quick talk through. I find I learnt an awful lot from listening but don't tell my Mum!

It was interesting that, in the absence of formally appointed or employed coaches, our participants established surrogate coaches through peer learning and teaching. Even more interesting was the extent to which, although they should be termed informal, the impact of these relationships were so powerful as to give them an almost formal feel. In fact, participants with experience of other sports drew this analogy themselves, for example "I would probably pay as much attention. . .hey, perhaps even more, to my friends at the skate park as I would to the stuff I get from my football coach." Alternatively, this participant highlighted "I've had a lot of coaches in the activities I've done up to now. I have to say that working with my friends is far more effective because they have a real understanding and feel for what we're doing" (Fransen et al., 2015).

Error Usage

Getting data on the use of this tool was notable in that almost all participants provided lots of information but, almost always, only after probing. Several spoke of the need to be accepting of errors, such as this rider: "You're never gonna be any ****ing good at this if you don't have lots of **** ups" or this,

> You've got to accept that you're going to take more than a few falls. . .it isn't great in front of your mates but to be honest the hardcore boys in here just accept it and even encourage you to have another go.

One big feature of the groups' learning strategies described below, was how participants used their peers, together with video feedback, to help them correct errors (Guadagnoli and Lee, 2004). For example, "My mates are great. They notice differences or problems, point them out and suggest changes," "If I do a run, especially if I'm trying for something in competition, I rely on my mates to help me look at the run [critically] and work out where I can make improvements" or finally from another participant:

> I think it's crucial to use your **** ups positively. I want to work out what I've done wrong and how to correct it. To do that, I use as many different inputs as I can. . .teammates, video, how it felt, the whole lot.

Error correction and the tools to do it were seen as particularly important for competition (cf. Poolton et al., 2005), as shown by this participant quote:

> I might be in something at the park where I've got the best of three runs. If I land the first one that's great. If I **** up, I need my mates and the video to help me get it right next time.

Practice

Unsurprisingly, practice was mentioned by almost every participant. Unsurprising because, for many, practising and refining their skills represented the whole joy of the activity in this aesthetically driven sport. Drilling, repeating moves over and over again, was a major feature. "I have to get my moves straight. I keep going and going 'til I just know I can do that move wherever I am."' Or this 16-year-old who seemed to be using a form of overlearning: "I have to have the basics. . .I have to be able to ollie [a jump up or on to a feature with the board] wherever I am." Interestingly, this desire for skill transfer did mean that participants would try out the same skills in a number of different sites, either within the same park or on trips to others. Importantly, however, especially against ideas like "repetition without repetition" (Bernstein, 1967), they would usually get this mastered in one situation before trying it elsewhere. "When I started, I hammered the stance-push-stop basics at home. Only then did I feel comfortable to go out to the park. . .to ride in public!"

Participants reported several different features common in other skill acquisition scenarios and also seemed to draw on ideas from other action sports. For example, as previously highlighted, whole-part-whole seemed important for those getting a sequence of moves down (Hanin et al., 2002). "I'll plan a run across the park then use that as the base for practice. I might do the whole run, then work the rail in the middle, then put it together and then go again." At a higher, session level, performers were very aware of setting up a theme or target for the day; some in advance but some in a more *ad hoc* fashion (see section "Programming and Planning" below). Interestingly the idea of push-drill-play, recently discussed in free skiing and snowboarding (Collins et al., 2018), seemed to resonate with participants even though they had seemingly never heard of the original idea. "Some days I'll get to the park and it's having it. . .I'm there on a mission. Other times I'll just go hammer one or two moves. Other times I'm just going to **** about with the guys."

Finally, as a small but distinct subcategory, there were several participants who just preferred to go on their own. These "solo performers" seemed to understand the sense in their peers using others, but it was just their personal preference to practice alone. For example, one 18 years old states:

> I've never been one for the crowd, especially when I'm putting new stuff together. Even when I started, however, I'd much rather go away on my own and get things sorted. It was almost like people being around were a distraction. . .or a challenge to what I was trying to achieve.

Programming and Planning

We have already mentioned participants' habits about making decisions on what they would do at each visit. Clearly, and in the absence of any formal designated coach, no written structures were apparent. Interestingly, however, participants themselves imposed structures mostly at micro or session level, as well as a meso (monthly) and macro (yearly) level (Bompa, 1983). From a micro perspective we would reiterate that, with certain exceptions, riders would usually arrive at the park with a predetermined plan; albeit that this might have been arranged on the bus journey to the park. One participant stated "I don't just like to turn up. Course it ain't like school but I want to know what I'm gonna get from being there, what I'm gonna do, even who I'm going to meet."

At the meso level, many participants used both vibing and prior discussion to develop at least plans of intent; an outline of what they wanted to achieve over the next few weeks. "I watch a lot of video and visit a lot of skateboarding websites and that gets me interested. It gets my juices flowing about what I want to try and achieve next." Or this 16 year-old: "I watch videos and websites but that's the sort of an external pressure of course. I also want to keep up with the leaders at [name of park]."

Macro level planning seemed to be apparent only in a minority of participants with a regular competition schedule or the view of getting involved in competing. "I know what comps I'm going for. . .it determines where I am, when and what I'm doing." Or this 18-year-old:

> I've really got into competing at skateboarding. I'd say that has taken over as my main motivation. I want to do well. . .I want to establish a reputation for myself and start getting some of my videos on Instagram or YouTube. I can see a genuine career in this.

Objective 1: Brief Discussion

Based on the analysis above, it is clear that participants use a variety of tools and skills to develop their ability in skateboarding. Perhaps most revealing from these data was a clear emphasis on cognitively oriented structures and processes. For example, the use of mental imagery was utilised from different perspectives, and for different purposes. Most notably, however, participants expressed that the "thinking through" of skills was a common feature of their initial understanding and the movements' continued execution. In this way, knowledge was considered to underpin progress, both in terms of the skill itself and as the rider's ability developed. As such, these data tend to support the development of individualised movement representations that provide a scaffold for interpreting information within the skateboarding environment, and for guiding the skill execution.

These explanations are well-aligned to the multi-level framework proposed by Schack et al. (2014). Data suggest that individual (lists of moves) and/or clustered (combinations of moves) elements of stored movement representations (Basic Action Components; i.e., knowledge of what to do) need to be integrated with coherent sensory representations of what the skill should "look like" (i.e., perceptual effect-representations) and mental control strategies (e.g., pre-performance routines) to provide a most elaborate/complete understanding of technique development (see Schack and Bar-Eli, 2007; Schack et al., 2014). Consequently, this framework would support the sensible use of both internal and external foci by performers to be able to fully understand and perform skills (Collins et al., 2016).

Despite this cognitive emphasis, data support a growing realisation within sport science and coaching research for an interactive understanding of processes and practices. In this particular case, the cognitive elements were expressly influenced by social factors. Importantly, who was observed within the park, the frequency of overt watching and the impression presented to others (i.e., the aesthetic of the skill) constrained the utility of mental skills. In summary, how riders learnt was reportedly grounded in cognitive mechanisms that were influenced by multiple environmental considerations.

Objective 2: Where They Learnt About Learning

As stated earlier, our interest in this particular participant group was the almost complete absence of formally appointed or explicitly recognised coaches. As the sections above demonstrate, however, there was clearly coaching in place and this process was both acknowledged and valued by our participants. Once we had explored early responses about how to get better, which initially were mostly related to technical aspects, we then managed to focus on why participants were practising in the way they were and where this might have come from.

There were many responses which fell into the tacit category (Nyberg, 2014). For example, this 16-year-old: "It felt comfortable watching and copying. . .I feel like I have done that my whole life." For these sorts of responses, participants seemed unaware of where the techniques had come from or unable to offer any rationale as to their use. Answers of the "it just does [work], so I use it" category were the most common with 58 participants (64%) responding in this way.

In addition to these, however, there were a number of perhaps more thoughtful participants who offered a greater depth of response. For many of those participants, ideas and approaches were transferred from their experiences of skill learning and practice in other environments. For example: "I guess I just think about the way we do it at school. It makes sense so I use it in the park." Or from this 16-year-old: "I used to go to both gymnastics and judo clubs and I guess how I practice here has been quite influenced by the stuff we did there." We obtained similar responses from 17 participants (19%).

Other participants reported gleaning techniques from websites, mostly in skateboarding but also notably in other similar action sports (Jones, 2011). "I've watched several videos on [skateboarding site] which have interviewed top riders. They all talked about imagery or visualisation as a technique. I tried it and it works." Or from a 16-year-old: "I've seen even the stars trying and failing a number of times, looks like they go away and hammer the practice, if it's good for them it'll work for me." Websites were mentioned by 16 from this sample (17%).

Finally, a small number of participants had actually sought out help from books, social media and websites specifically on the pedagogic principles. "I got this book for Christmas that talked about coaching and pretty much that became my Bible." Or "I get great ideas from social media sites and blogs on coaching. . .I try them and if they work, I add them to the mix." This more "academic" approach was apparent in 12 of this sample (13%). As should be clear from the totals, some responded in more than one category.

Objective 2: Brief Discussion

Many other action sports already operate within a formal coaching culture, albeit that those coaches have usually received training in another, more traditional sport, then transferred these skills into the new activity, supplementing it with books, internet-based knowledge and communities of practice (Collins et al., 2019). Similarly, a proportion of participants expressed a desire to develop their knowledge further, predominantly using sources of the same nature, such as websites and social media. This further highlights the importance for coaches offering information on these sources to consider both quality and bias (Stoszkowski and Collins, 2016). For example, high-level coaching must consider the age and stage of specific learners, in this case youths, and the extent to which generic online material is most appropriate for these participants. It may well be that a combination of "expert" modelling prior to practice, followed by a combination of "self," "coping," or "self-coping" models offer a better long-term solution; in short, it depends!

Objective 3: Top-Enders

Finally, we were able to interview nine individuals of the 11 top-enders identified. It would be wrong to define these individuals as experts. We applied no performance criteria and their "appointment" to this status was clearly context specific and based on group perception. That said, there were several differences in the practice behaviours of these individuals which, whether causative of, or associated with, their status, seem worthy of note. Results were extremely similar to the other participants, with one or two notable exceptions. Firstly, 100% were keen and consistent consumers of external sources (social and other media) on skateboarding. "I need to look at the sites at least twice a week to stay up to speed. . .it's where I get my edge," "I want to see what others are doing – the ideas help me to improve and also direct my practice." Original ideas were usually sourced from other environments whilst only a few were genuinely creative in focus.

As a second difference, top-enders seemed almost "error seeking" in their exploration of new alternatives (Hodges and Lohse, 2022). "If I can do it this way then why can't I do it that way. . .if someone else is doing it like this then why can't I do it like that" or "I'm always looking to do the new and peculiar especially when it comes to putting moves together."

Finally, these participants seemed a lot more self-driven and experimental in their activity (Mallett and Hanrahan, 2004). "I tend to set myself some clear targets, but these are based on what I want to achieve. . . it's all about me!", "When I come to the park, I tend to play with purpose. . .to just **** around to see what I can come up with." Or this 21 years old (one of the elder statesmen) "Things have changed as I've got older; I used to watch the others all the time; picking out a guy or a trick that I wanted to copy; but not now."

Objective 3: Brief Discussion

Against this objective, the exploratory nature of these responses are similar in this regard to that of expert breakdancers, reported by Shimizu and Okada (2018). Notably, these local leaders appeared to be far more committed "students" of their sport, when compared with other participants. Evidence of information-seeking beyond their immediate domain, in order to stay ahead or provide an edge to performance, reflects present understanding of creative expertise (Mishra et al., 2015). As with the previous objectives, these participants' account of their practice were grounded in cognitive processes, often developing a more detailed and in-depth analysis of their skills.

GENERAL DISCUSSION AND RECOMMENDATIONS

The objectives of this study were to explore how skateboarders learn new skills in the absence of formal coaching and establish how and from where these skateboarders gain coaching insights. Finally, to identify how and/or why "top-enders" were more successful. Overall findings revealed that participants utilised a number of tools and aids to acquire and enhance their skills, often sourced socially (through both media and peers; Jones, 2011) and interpreted by participants through a cognitive perspective of learning (Schack et al., 2014). Following our brief discussions above, there are a number of important points of discussion that could usefully inform the coaching literature.

Firstly is the perceived theoretical underpinning of learners' development as being largely cognitive in nature. Not only did this relate to the way in which learners practiced, but also the knowledge they acquired to help consolidate skills away from the park. Clearly, this perspective is in contrast to opposing ecological approaches (something we will come onto below), but data are also contradictory of approaches *within* the cognitive paradigm and promoted in sport coaching literature (Winkelman, 2017). Specifically, participants reported the active use of cognition to understand, develop and control their movements in pursuit of higher skill levels. Such a mechanism of learning is counter to that promoted by implicit motor learning, which suggests that learners practice under conditions to actively prevent the accrual of knowledge pertaining to the technique to avoid subsequent breakdown under pressure. For example, this approach would promote practice without errors and/or dual-task conditions to consume working memory with task-irrelevant information (Poolton et al., 2005; Gabbett and Masters, 2011). Indeed, the relevance of implicit motor learning has recently been raised as an ill-considered approach to learning complex sports skills (Bobrownicki et al., 2019) and would appear to not reflect the way in which these participants told us that they learnt. Therefore, despite being underpinned by the cognitive approach, we would suggest caution toward any recommendation of implicit methods that are currently popular within some coaching communities.

In support of active conscious control as an underpinning mechanism of learning and skill execution, training by the performers resembled the use of "contrast drills." Previous studies have explained that the aim is to compare and contrast an existing and desired movement version by generating a new alternative and then consciously distinguishing between the two; in turn, this differentiation serves to create a realisation of the change required (Carson and Collins, 2011). Central to this process is an athlete's understanding of the movement, before internalising the changed component to subconscious control (Carson and Collins, 2011). This could be seen, for example, during the use of errors, which participants used as tools to develop understanding by better realising what they were trying to avoid (Light and Harvey, 2015). While a large majority of research in sport coaching and motor learning has focussed on practice schedules such as blocked and random practice (e.g., Lage et al., 2015), the use of contrasts at this stage of learning is relatively, if not completely, absent and presents a beneficial development within the coaching literature.

Furthermore, the reported use of attentional control within these data was expressed as a dynamic process in both direction and purpose. Sometimes, focus was on the skill production (i.e., what the movement looked like) and then switched internally (i.e., what the movement felt like) once the performer had identified the movement(s) of interest; representing the switch from "attention" directed externally within the environment to an internal state of "intention" to retrieve the movement from memory, as seen in many target sports prior to skill execution (e.g., Hatfield et al., 1984; Loze et al., 2001). Indeed, the common use of "watch then image" before "doing" as a method is very similar to ideas suggested in karate by Smith et al. (1997) and recently examined in darts by Romano-Smith et al. (2019). The combined use of alternated observation and imagery was commonly reported as offering a means to "internalise" what was being watched (cf. Hall et al., 1998; Fournier et al., 2008). We did not probe on the modalities of this process, on the basis that the explanation of constructs would have been too theoretically leading. Notably, however, observation of several participants (watch – look away – watch – repeat) was highly suggestive of the external visual *then* internal kinaesthetic strategy suggested by Smith et al. (1997). In fact, recent research into the mirror neuron system would suggest that the extent of neural activation during this perceptual process to be enhanced with improvements in the skill execution itself (Calvo-Merino et al., 2006). In other words, as the performer's ability to empathise with the experience of the model increases, so too does the quality of information extracted from the observation and, in turn, ability to use it for memory retrieval purposes. Overall, data from participants suggests that research should explore mental strategies as non-dichotomous constructs when seeking to understand how they can usefully benefit learning and performance (cf. Wulf, 2016; Collins, 2021).

From a physical perspective, participants reported the almost ubiquitous use of drilling, comprising of many repetitions of the same skills. Such practice is commonly associated with traditional information-processing approaches to learning (Williams and Hodges, 2005), however, the use of errors expressed by participants suggests that even in this context the repetitions were not the same and therefore would not constitute effective practice. This concept is, however, congruent with the "repetition without repetition" (Bernstein, 1967) notion synonymous with dynamical systems theory (Kelso, 1995) whereby variability in execution is deemed a positive attribute for future adaptability. Recent advances in this thinking, however, have posited that the degree of repetition across the different movement subcomponents is differentially meaningful (Scholz and Schöner, 1999). For clarity, some elements of the skill should be trained to purposefully demonstrate more consistency than others *because* they are important to achieving the desired outcome. Whether or not these, or most probably the other, movement subcomponents could be considered as being self-organised is beyond the scope of this paper. Our data suggest, at least, that participants understood their cognitive intentions when repeating a skill as contributing toward movement effectiveness of those subcomponents; that is, what the performer was trying to work on became more consistent across repetitions. Accordingly, motor skill development may be better considered as a blend of cognitive and non-cognitive processes (e.g., ecological direct perception) interacting within and across each repetition (cf. Collins et al., 2021). As such, coaches should consider *what* they ask their performers to focus on *and* the extent to which the training regime promotes variability to support the flexible execution of non-essential movement subcomponents.

Irrespective of the motor control perspective taken (cognitive or ecological), data pointed toward a clearly complex and biopsychosocial learning processes for participants. For example, considering a social perspective to what participants reported, in the absence of formal coaching, participants held in high esteem acted, with perhaps equal effect, as surrogate or peer coaches. The only barrier to seeking "formal" coaching status appeared to be social embarrassment, or perhaps ego! Indeed, social dynamics within the park also heavily impacted on the use of practice and learning tools. Jackson and Beauchamp's (2010) work on metaperception within athlete-athlete relationships is relevant here, because it highlights the importance of understanding relationship dynamics as another key factor in response to coaching buy-in. In other words, getting better at performing the skills (Bio), is enhanced by identifying and extracting task-relevant information from a model (Psycho), which is more likely when that model is highly valued (Social).

Of course, and again reflecting the biopsychosocial nature of learning, there were individual preferences amongst participants that coaches should consider. This aligns with the suggestions from Ellmer et al.'s (2020) scoping review which highlighted the individualistic and typically self-regulated nature of learning in sports similar to skateboarding. As suggested by Nokes-Malach et al. (2015), self-identified solo learners seemed to suggest that others "got in the way" or made them "feel too busy!" These attitudes, along with several identified in the present study (e.g., feeling responsible to push themselves as an independent "top-ender"), need to be considered by coaches in offering more nuanced approaches toward performer development.

Finally, it is worth considering the further comments offered by one of the SMEs in relation to how a coach's knowledge/understanding of participants could positively impact on potential biopsychosocial interactions. Thompson expressed:

> The language used in responses from the skateboarders was of interest to me, phrases such as "I want to understand" and "I really want to know." This got me thinking about curiosity and the role it plays within the learning process. In particular, how curiosity can drive progression and therefore the risks of coaching not nurturing ones natural level of curiosity (S. Thompson, personal communication, 28th November 2020).

It seems clear that Thompson, an experienced coach in a pursuit not dissimilar from skateboarding, expresses the importance of understanding as part of the skill acquisition and developmental process. He went on to explain that a key feature of this understanding exists due to the nature of the physical pursuit.

> I see this on a daily basis working with my current athletes. The more curious an athlete is about an area of performance the more they are willing to delve into it to seek performance gains. This becomes even more apparent when the level of risk is high, especially in progressive sports like skateboarding and snowboarding. Once the curiosity is there, the "whatever it takes" mindset kicks in and the reward of landing a new trick out values the risk of injury (S. Thompson, personal communication, 28th November 2020).

Conclusion and Implications

This study was designed to explore a modern youth phenomenon; namely, unstructured and non-directed practice in an informally/socially judged activity. The main purpose was to see how young people learnt skills in an activity when it was "coach-free." There were clearly many different and often contrasting ideas with existing literature, however, perhaps the clearest idea to emerge is the necessity for coach decision making to be contextually driven and focussed on both the needs and preferences of the learners (cf. Vinson and Parker, 2019). Regarding the choices about, and applications of, learning strategies in these coach-free performers, participants predominantly reported cognition to underpin their learning, in addition to social factors as important to enacting these mechanisms. Of course, however, the coaching tools reported by the participants may also be suggested as representative of an ecological approach, through the use of constraints for example (e.g., FTN, 2020). In any case, a performer's learning preferences are likely a socially constructed phenomena, and therefore all previous research which has sought to support a particular coaching approach has been influenced by this. Therefore, it seems sensible that research should look to explore in greater detail the preferences and behaviours of performers who have been conspicuously absent from these influences. Moreover, we would welcome data from a range of methodological approaches, but encourage researchers to consider the purpose of their research and whether or not it *can* relate to and directly translate to the learners/coaches involved.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the University of Central Lancashire. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

RC ran the project and contributed to leading on ethics submission, data collection, data analysis, and write up. DC supported in data collection, collected all the data in the second country, and wrote the final manuscript. HC acted as a critical friend throughout the data analysis process, insured maximum rigour throughout the process, and supported significantly with the write up of the article. All authors contributed to the article and approved the submitted version.

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Real-World Walking Speed Assessment Using a Mass-Market RTK-GNSS Receiver

Luca Reggi[1], Luca Palmerini[1,2]*, Lorenzo Chiari[1,2] and Sabato Mellone[1,2]

[1]Health Sciences and Technologies-Interdepartmental Center for Industrial Research (CIRI-SDV), University of Bologna, Bologna, Italy, [2]Department of Electrical, Electronic, and Information Engineering "Guglielmo Marconi", University of Bologna, Bologna, Italy

Walking speed is an important clinical parameter because it sums up the ability to move and predicts adverse outcomes. However, usually measured inside the clinics, it can suffer from poor ecological validity. Wearable devices such as global positioning systems (GPS) can be used to measure real-world walking speed. Still, the accuracy of GPS systems decreases in environments with poor sky visibility. This work tests a solution based on a mass-market, real-time kinematic receiver (RTK), overcoming such limitations. Seven participants walked a predefined path composed of tracts with different sky visibility. The walking speed was calculated by the RTK and compared with a reference value calculated using an odometer and a stopwatch. Despite tracts with totally obstructed visibility, the correlation between the receiver and the reference system was high (0.82 considering all tracts and 0.93 considering high-quality tracts). Similarly, a Bland Altman analysis showed a minimal detectable change of 0.12 m/s in the general case and 0.07 m/s considering only high-quality tracts. This work demonstrates the feasibility and validity of the presented device for the measurement of real-world walking speed, even in tracts with high interference. These findings pave the way for clinical use of the proposed device to measure walking speed in the real world, thus enabling digital remote monitoring of locomotor function. Several populations may benefit from similar devices, including older people at a high risk of fall, people with neurological diseases, and people following a rehabilitation intervention.

Keywords: real-world walking speed, remote monitoring, global navigation satellite system, real-time kinematic, validation

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Steven van Andel, University of Innsbruck, Austria

Reviewed by:
Yun-Ju Lee, National Tsing Hua University, Taiwan
Richard Bohannon, University of Connecticut, United States

***Correspondence:**
Luca Palmerini
luca.palmerini@unibo.it

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INTRODUCTION

The ability to move is a feature that characterizes most of the animal kingdom because it plays a critical role in finding food, escaping danger, and surviving. Notably, generalized slowing of movement is associated with aging (Studenski, 2009). Even for humans, where these primordial tasks are less important, the capacity to move is essential to maintain independence in daily activities (Yildiz, 2012) and good quality of life (King et al., 2013). From a physiological point of view, locomotion is a complex matter involving the following systems: nervous (central and peripheral), perceptual, muscular, and skeletal. It is also influenced by how energy is produced and delivered (Ferrucci et al., 2000). One of the most significant parameters summarizing the ability to move is walking speed (WS) (Abellan Van Kan et al., 2009), a valid, sensitive, and specific measure (Fritz and Lusardi, 2009). It is widely used as a predictive tool for future adverse outcomes such as disability

(Newman et al., 2006), shortened survival time (Studenski, 2011), institutionalization (Montero-Odasso et al., 2005), worsening health status (Studenski et al., 2003), and falls (Guimaraes and Isaacs, 1980). Walking speed reflects both functional and physiological changes (Perry et al., 1995).

For this reason, it is useful to evaluate the effects of rehabilitation (Goldie et al., 1996). In fact, several medical fields such as neurology, geriatrics, orthopedics, and cardiology assess WS (Graham et al., 2008). A WS measurement can be part of a more structured and validated performance test (Schimpl et al., 2011) (e.g., Short Physical Performance Battery and Time Up and Go), or be used as a single measure, especially for predictive purposes (Hardy et al., 2007).

The WS is primarily assessed over short distances (both for ease and speed of execution), typically four or 10 m (Graham et al., 2008); a stopwatch is used to measure the time taken to travel the assigned distance. The measure is performed predominantly in a controlled environment. While this setup is prevalent and validated, some studies have pointed out the poor ecological validity of assessing WS in an environment like a hospital or clinical facility (Moseley et al., 2004; Stellmann et al., 2015). In fact, unlike walking in real life, the distance is limited, and the environmental conditions are relatively unvarying. As a result, different technologies, like inertial measurement units (IMU) or global positioning systems (GPS), have been used to measure walking speed continuously in daily life. The latter solution offers distinct advantages, as it allows to have a direct and continuous measurement of WS without the need for integration (e.g., accelerometer) (Gernigon et al., 2015) or supervision (Gernigon et al., 2014). Besides WS, it allows, using the absolute position, an assessment of different types of mobility patterns (Fillekes et al., 2019) (e.g., for epidemiological studies (Klous et al., 2017)). Previously, Le Faucheur et al. (2007), Townshen et al. (2008), and Noury-Desvaux et al. (2011), tested the accuracy of portable, low-cost stand-alone GPS devices in measuring walking speed in environments with complete sky visibility (e.g., outdoor running track, public park free of buildings and dense trees), obtaining promising accuracy. One of the major limitations of such devices, however, is that their accuracy decreases in environments where obstacles obstruct sky visibility (like under trees or near high buildings) and becomes very low when used indoors. Still, those environments with decreased visibility are also very important for a real-world evaluation of walking. One technique that increases the system's accuracy, especially in the situation of decreased sky visibility, is the Real Time Kinematic (RTK) modality, based on the use of two communicating GPS receivers to obtain a differential solution (which standard stand-alone GPS devices cannot perform). This technique is not new, but until a few years ago only bulky, very expensive (>1000 €) survey-grade receivers were available. Recently, the mass-market production of RTK-capable chipsets has reduced costs and dimensions while ensuring good accuracy (although lower than professional receivers).

This work aims to assess the suitability of a mass-market RTK receiver to measure real-world walking speed (RWWS), in a challenging environment with different degrees of sky visibility. To do so, the data from the RTK receiver is processed as detailed below and compared with values obtained from typical reference systems for these kind of studies (an odometer and a stopwatch).

FIGURE 1 | Device set-up: simpleRTK2B, antenna, power bank, and smartphone.

MATERIALS AND METHODS

Instrumentation and Data

The tested device is a low-cost (~250€), dual-band, multi-constellation RTK-capable receiver called simpleRTK2B (Ardusimple, Spain), based on the chipset ZED-F9P (u-blox). This device was the first mass-market receiver with upper and lower L-band coverage for all major constellations of GPS, GLONASS, Galileo, and BeiDou satellites, collectively known as GNSS (Global Navigation Satellite System). The RTK technology is based on the communication between two receivers, a base, and a rover. The base receiver, located in a fixed, known position, can calculate the error between its actual position and its position as estimated by the GNSS. If the base and rover are close enough (less than 30 km), they suffer the same environmental errors, so the rover can use the error calculated by the base as a differential correction to improve its accuracy.

The receivers communicate through the internet as caster and client, using the NTRIP protocol (Dammalage and Samarakoon,

TABLE 1 | Data extracted from NMEA sentences.

Description	Source	Format	Units
Latitude/longitude	RMC	ddmm.mmmm/ dddmm.mmmm	Degrees and decimal minutes
UTC Time	RMC	hhmmss.sss	Hour, minute, second, millisecond
Speed over ground	RMC	—	knots
Status: presence of the solutions	RMC	'V' for void or 'A' active	—
MLS altitude	GGA	—	m
Age of differential corrections: seconds since the last update of the corrections by the References station	GGA	—	s
Horizontal dilution of precision (HDOP): effect of navigation satellite geometry on positional measurement precision	GGA	—	—
Satellites used: number of satellites used in the solution (for the NMEA format, the maximum number is 12)	GGA	—	—
Position fix indicator: modality in which the device calculated the solution (RTK, float RTK, DGPS, or GPS: defined below)	GGA	—	—

2008). In our study, the simpleRTK2B worn by the participants acted as the rover. We used a reference station (part of the EUREF permanent GNSS network) that offers a no-fee caster service as the fixed base. The base station, located in Medicina (BO, ITA), uses a LEICA GR25 receiver situated about 25 km away from the testing location (Costa-Saragozza district, BO, ITA). We used the Lefebure NTRIP client application, installed on a smartphone (Oneplus 6) and connected to the receiver through Bluetooth, to receive the differential corrections and log the NMEA sentences obtained from the receiver (u-bloxF9HPG, 2021).

The rover setup comprised the simpleRTK2B (weight: 100 g; dimension: 68 × 53 mm) wired with an antenna (ANN-MB series, u-blox, weight: 200g; dimension: 60 × 55 mm) and powered by a power bank (see **Figure 1**).

We were interested in extracting only two NMEA sentences from the RTK rover: the RMC (Recommended Minimum Specific GNNS Data) and GGA (Global Positioning System Fixed Data). For this reason, we set the device to output only these sentences, at the minimum sampling period allowed, 55 ms (18.18 Hz). From these sentences, we extracted the data shown in **Table 1** for each sample.

The number of satellites used, the age of the differential corrections and the HDOP (Horizontal Dilution Of Precision) were recorded to monitor the receiver's functioning during the acquisitions. However, since their values were almost always constant and good, they will not be presented in the following analysis. Also, the altitude is not mentioned further because the test took place in a flat area.

The device can work in different modalities (called position fixed indicator) with different qualities (and corresponding degrees of accuracy). This is because calculations are performed differently for different modalities. Each modality is summarized here in descending order of accuracy (quality):

1. RTK: differential technique based on carrier signal with an integer resolution of the integer ambiguity (Teunissen, 2003).
2. Float RTK: differential technique based on carrier signal with a float resolution of the integer ambiguity.

FIGURE 2 | Set-up of a participant.

FIGURE 3 | Image taken from Google Earth showing the 1300-m path (red line) and the start and end points of each walking tract (white pins). Description of the tracts: 1–5 park (open sky), 6–9 arcades (totally obstructed visibility), 10–12 bicycle lane (open sky with a few trees), 13–17 bicycle lane under tall trees, with tall buildings on both side (highly obstructed visibility), 18–24 sidewalk with tall buildings (partially obstructed visibility), and 25–26 park (open sky with a few trees).

3. DGPS: differential technique based on code signal.
4. GPS: single-point positioning, stand-alone functioning. For a more detailed explanation, please refer to (Kaplan and Hegarty, 2005).

Experimental Protocol

Seven healthy adults, five males and two females (age: 32 ± 6 years, height: 174 ± 14 cm), were recruited for this study after giving their informed consent. The acquisitions were all made on the same day (from 9:30 a.m. to 2 p.m.), with sunny and cloudless environmental conditions. Participants had the device in a backpack with the antenna on it (see **Figure 2**), similarly to previous studies (Le Faucheur et al., 2007; Noury-Desvaux et al., 2011). To test the accuracy of the device in different operating conditions, we defined a flat, 1300-m loop with different sky views (see **Figure 3**): open sky (park); open sky with few interferences (few trees), highly obstructed (under tall trees with buildings on both sides), and totally obstructed (under arcades). **Figure 3** shows a photo of the path with pins describing the start and endpoints of the 26 tracts (each tract is described by two pins, e.g., tract 1 is between pin 0 and 1). This area is in the Costa-Saragozza district of Bologna (lat: 44.495,280°, long: 11.312,900°). Participants started walking in an open field to allow the device to operate with the highest accuracy possible and then walked 26 tracts of approximately 50 m (49.9 ± 1.7 m) at a comfortable pace while carrying the backpack and an odometer (STANLEY MW40M, accuracy 1 dm). This instrument accurately measured the distance and showed the participants and the examiner when they had walked 50 m and had to stop. An examiner walking beside the participant timed each tract with a stopwatch (Finis 3 × 100M, accuracy 1/100s). At the end of each tract, when the examiner instructed the participant to stop, the examiner noted down the elapsed time, and the distance traveled.

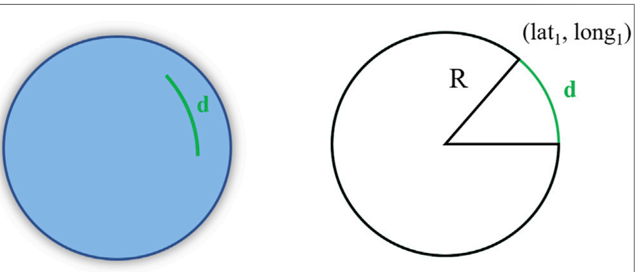

FIGURE 4 | Graphical explanation of the haversine formula.

Data Processing

First, we discarded the sentences with 'V' in the RMC status field, indicating the receiver did not obtain a result. This can happen for many reasons, like very poor coverage. We converted latitude, longitude, time, and velocity from the NMEA formats to degree, DateTime format, and m/s, respectively. By manually inspecting the raw velocity signal, we found the start and end of each 50-m tract and extracted the walking sessions from the resting periods for a total of 182 (26 × 7) sessions whose average speeds could be compared. We calculated the elapsed time, and the distance traveled for each walking session. The distance was calculated as the line integral between the start and end of the walking session. More precisely, we summed all the distances (D) calculated between each position sample (lat, long) using the haversine formula:

$$D = 2*R*arcsin\left(\sqrt{sin^2\left(\frac{lat_1 - lat_2}{2}\right) + cos\,(lat_1)*cos\,(lat_2) *sin^2\left(\frac{long_1 - long_2}{2}\right)}\right) \tag{1}$$

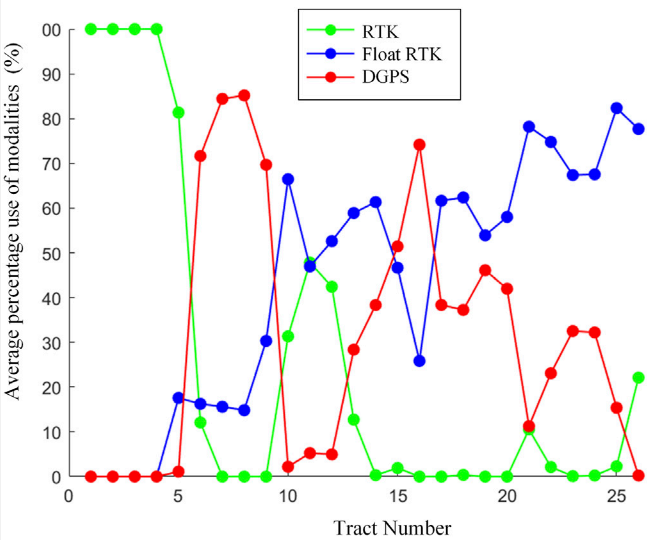

FIGURE 5 | Average percentage use of the different modalities in each track.

TABLE 2 | Walking speed values obtained from the RTK and the reference systems.

Participant	simpleRTK2B Speed, m/s (std) [Range]	Reference Speed, m/s (std) [Range]
1	1.55 (0.07) [1.44–1.72]	1.59 (0.06) [1.47–1.68]
2	1.50 (0.07) [1.37–1.64]	1.55 (0.05) [1.46–1.69]
3	1.32 (0.06) [1.18–1.48]	1.37 (0.06) [1.17–1.47]
4	1.40 (0.06) [1.27–1.49]	1.47 (0.04) [1.37–1.56]
5	1.48 (0.10) [1.24–1.65]	1.56 (0.08) [1.33–1.67]
6	1.43 (0.12) [1.24–1.71]	1.51 (0.10) [1.27–1.66]
7	1.52 (0.08) [1.32–1.63]	1.58 (0.05) [1.45–1.66]
Tot	1.46 (0.11) [1.18–1.72]	1.52 (0.10) [1.17–1.69]

The average walking speed, its standard deviation (std), and range [min–max] for both the simpleRTK2B and reference systems, considering all 26 measurements from each subject. In the last line (Tot), values are calculated considering all the tracts of all the participants.

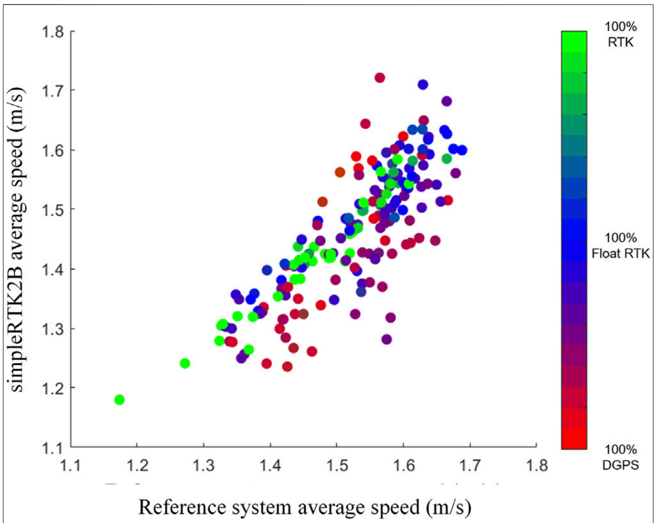

FIGURE 6 | Scatter plot of the average walking speed (*x*-axis reference, *y*-axis GPS). The color map represents the RGB triplets associated with the relative frequency of the three working modalities in each tract (RGB) = (n° DGPS, n° RTK, n° float RTK).

where *R* is the radius of the earth (6,371 km), *lat* is the latitude and *long* is the longitude of each of the two points between which we calculate the distance (see **Figure 4**).

We calculated the average RWWS measured by the simpleRTK2B as the distance walked divided by the elapsed time. We chose this method to be consistent with the odometer reference system, which uses the same formula. In fact, for the reference values, the distances obtained from the odometer were divided by the times obtained from the stopwatch.

Statistical Analysis

The comparison between the average RWWS measured with the simpleRTK2B and the reference system was performed using the Pearson's correlation coefficient to measure the linear association between the two sets of data, the R-squared value to quantify the explained variance, and the Bland-Altman analysis (Bland and Altman, 1999) to test the agreement between the two systems. The minimal detectable change (MDC) was also calculated to measure the system's accuracy. It was calculated as one-half the difference between the Bland-Altman plot's upper and lower agreement limits (Haghayegh et al., 2020). Finally, to better understand the relationship between the accuracy of the measurement and the different working modalities, which are influenced by the degree of visibility of the sky in the different tracts, we repeated the same analyses on two subsets of the data. These cases were created by discarding all the values obtained in tracts with the percentage of DGPS solutions (the least accurate modality achieved during the study) above 50 and 25%, respectively.

A bootstrap analysis (using random sampling with replacement repeated 100 times) was performed to evaluate the confidence intervals of the obtained metrics. It was also used, together with one-way analysis of variance (ANOVA) and Tukey-Kramer test for multiple comparisons, to evaluate significant differences between the three cases (the full dataset and the two subsets with different quality thresholds).

The analyses were performed in Matlab (R2020a).

RESULTS

During the experiment, the device worked in three modalities (RTK, float RTK, and DGPS) for 23.8%, 43.4%, and 32.8% of the time, respectively. It never worked in the GPS modality. The behavior of the simpleRTK2B receiver in the different tracts of the path is described in **Figure 5**, which shows the average percentage usage of the three modalities achieved for each tract. The RTK modality (highest quality) is the most

TABLE 3 | Summary results.

	Pearson's Coefficient [CI]	R-squared [CI]	MDC (m/s) [CI]	Total Number of Discarded Tracts	Number of Tracts Discarded by Participant (mean ± std)	Number of Tracts where WS is Calculated
All values	0.82 [0.77 0.88] *	0.67 [0.59 0.76] *	0.12 [0.11 0.14] *	0	0	182
DGPS <50%	0.9 [0.84 0.95] *	0.81 [0.71 0.90] *	0.09 [0.07 0.11] *	52	7 ± 2	130
DGPS <25%	0.93 [0.91 0.96] *	0.87 [0.82 0.93] *	0.07 [0.06 0.09] *	90	13 ± 3	92

*Summary of the computed metrics for the three cases: values from all tracts, values from tracts with <50% DGPS solutions, and values from tracts with <25% DGPS solutions. The MDC is calculated as one-half the difference between the upper and lower limits of agreement of the Bland-Altman plot. CI: 95% confidence intervals obtained with bootstrap sampling; * significant difference (*$p < 0.001$*) from both the other groups.*

difficult to obtain, and, as expected, it is mostly achieved in tracts with open sky visibility (for example, tracts 1–5 and 10–12). On the other hand, as expected, the DGPS modality is mainly present in tracts with total obstructed sky visibility like arcades (tracts 6–9) or poor visibility due to tall trees and/or buildings (tracts 14–20). Instead, the float RTK modality is often present across all tracts, especially in tracts with a partially obstructed sky view.

Another aspect worth mentioning about the device behavior is the low number of empty results from the device (discarded in pre-processing). Out of 82,171 walking samples, only 95 (0.1%) were discarded, and 64 of them belonged to a single participant (Participant 1). As expected, 93% of these data points happened while the participants were under the arcades.

The two obtained walking speed datasets (simpleRTK2B and reference system), and the related scatter plot are presented in **Table 2** and **Figure 6**. In **Figure 6**, color represents the average quality of the tract in which that speed calculation was performed.

The Pearson's coefficient, the R-squared, and the MDC obtained from the Bland-Altman analysis are shown in **Table 3**, divided into the three cases considered (full dataset and the two subsets with different quality thresholds). For the two cases in which the quality threshold is applied, the number of discarded tracts, the average (±std) number of tracts discarded for each participant, and the remaining tracts in which WS is calculated are also reported.

Lastly, **Figure 7** presents the Bland-Altman plots with the average difference values and the limits of agreement for the three cases.

DISCUSSION

Multiple reasons led the device to work in the different modalities presented above, such as the base station receiver type, coordinate accuracy, number of available satellites, environmental factors, and operating range.

Within the environmental factors, in this work we mainly considered landscape-related factors, such as trees and buildings, which may obstruct the signal and lead to multipath interference (reception of reflected signals). The path selected for the acquisition offered different-use scenarios typical of a city, like tall buildings, arcades, and trees which entirely or partially obstructed visibility (obstructions could also be underpasses or hallways between buildings). On the other hand, the path also presents tracts with open sky typical of a city park and situations of mild interference. Such a heterogeneous scenario is an excellent and challenging test for a GPS receiver.

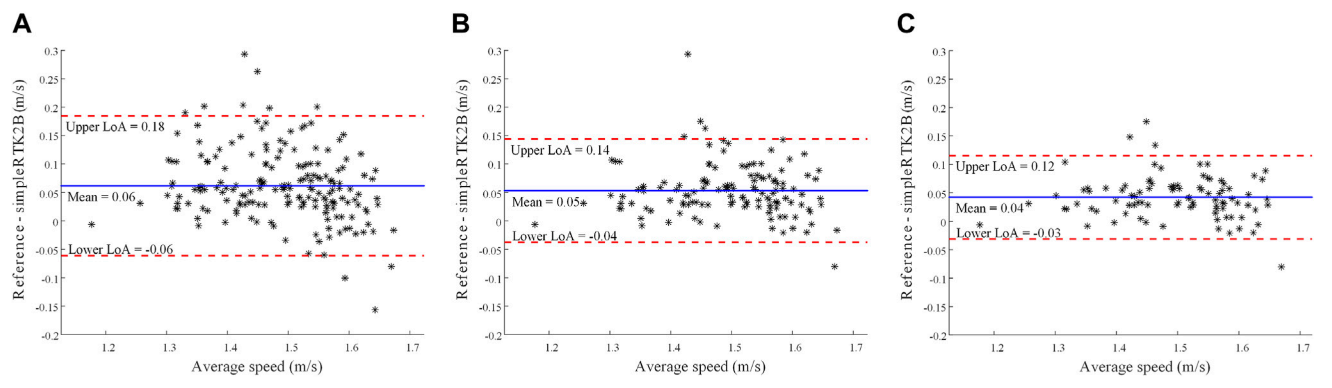

FIGURE 7 | Bland-Altman plots considering all tracts **(A)**, tracts with <50% DGPS solutions **(B)**, and tracts with <25% DGPS solutions **(C)**. The mean difference and the upper and lower limits of agreements (LoA) are reported.

First, it should be noted that although a tiny percentage of invalid points occurred in the tracts with high interference, the simpleRTK2B never selected the lowest-quality modality (GPS), which is a single-point positioning modality that would be equal to standard GPS stand-alone devices. Instead, the device always worked in a differential configuration. This result reflects the advantage of using an RTK receiver instead of a classic stand-alone GNSS logger or a smartphone for monitoring purposes since the differential modality leads to better accuracy than single-point positioning. Considering that among the differential modalities, the RTK is better than DGPS,, another positive aspect is that the device worked for 43.4% in float RTK and for 23.8% in RTK.

The comparison with the reference system shows a pretty good correlation (Pearson's coefficient of 0.82), even though the GPS receiver tended to underestimate the RWWS, as we can see in **Figures 6**, **7** and **Table 2**. This tendency is higher for speed values obtained with lower accuracy (red and violet shades in **Figure 5**).

When applying the two quality thresholds, the correlation coefficient increases to 0.93. If we look at the scatter plot, we can see that the green and blue points tend to be closer to the equality line. Similarly, for the R-squared values, the explained variance goes from 0.67 to 0.87 using the quality thresholds. This statistically significant improving trend (correlation and R-squared values are significantly higher, as expected, with higher quality) demonstrates how the different sky visibilities influence the system's functioning.

The MDC obtained was 0.12 m/s in the general case, with [0.11 0.14] as confidence interval. A recent review (Bohannon and Glenney, 2014) found minimal clinically important differences (MCIDs) for comfortable speed to be in a range between 0.1 and 0.17 m/s for various pathologies. Previous studies also indicated that an improvement or decrease of 0.1 m/s is related to positive or negative health outcomes, respectively (Purser et al., 2005; Hardy et al., 2007; Fritz and Lusardi, 2009). Therefore, the obtained MDC for the general case (and corresponding confidence interval) is in line with the reported MCID values, indicating a promising capability in identifying a clinically meaningful change in walking speed. Furthermore, the values, 0.9 m/s and 0.7 m/s, achieved from the two higher quality subsets of data perform even better, being under the reported MCID range, with the latter having the whole confidence interval below the range. The MDC is significantly lower (as expected) with higher quality.

One aspect to consider about these results is that the MCID are obtained from measurements conducted in the laboratory setting and not in the real-world environment, where values of MCID of walking speed are still not known. Further studies should consider how/whether the reported MCID values would change in the real world.

So, the procedure of applying a threshold on the quality of the tracts could be useful to increase the system's accuracy in obtaining the average speed of the entire path. Still, it could be argued that by applying this threshold, some tracts are discarded from the computation, and this could be a problem if the presence of discarded tracts is significant. Further studies on this aspect may be needed.

The results of the agreement analysis are in line with the ones obtained by Le Faucheur et al. (Le Faucheur et al., 2007), who used a low-cost non-differential stand-alone GPS. Also, they tested the device on an outdoor running track, which has complete sky visibility, while we tested the presented device in an environment with different degrees of sky visibility and interference.

In our study, the Bland Altman plots underline a small (between 0.04 and 0.06 m/s) positive bias that may be due to a systematic error related to the characteristics of the acquisition protocol (e.g., time estimation with a stopwatch).

The obtained results demonstrate the feasibility and validity of the presented device for the measurement of real-world walking speed, even in tracts with high interference. The main advantage of such device, with respect to other devices currently used for real-world walking speed estimation such as IMUs (Mazzà et al., 2021), is the fact that a wide set of additional measures and metrics (not measurable by an IMU) can be obtained. GPS devices in fact can provide, thanks to their localization capabilities, quantitative information on several aspects characterizing daily mobility such as life space (Fillekes et al., 2019; Taylor et al., 2019), out-of-home activities (Fillekes et al., 2019; Haeger et al., 2022), active transport modes (Fillekes et al., 2019), trajectories (Ziepert et al., 2021), distances from specific points (or participants) (Ziepert et al., 2021), time spent indoor/outdoor (Bayat et al., 2022), and type of activities (e.g. medical or sport-related) (Bayat et al., 2022).

The first limitation of this study is that we only tested a single weather condition (sunny and cloudless). This allowed us to focus on the effect of landscape interference, but further studies are needed considering interference from different weather situations (e.g., cloudy vs. sunny), which can also affect the system's accuracy.

Another limitation of this study is the small sample size which was used for this exploratory study. Larger sample sizes should be considered in future studies. A further limitation is that only healthy adults were considered, although this is common to most studies using GPS devices for walking speed estimation, except from two exploratory studies where a non-differential GPS was used to evaluate walking speed in people with Multiple Sclerosis (Delahaye et al., 2021) and people with claudication (Gernigon et al., 2014).

As a further future development, the reference system could be improved to be more independent from human error than a stopwatch, although this kind of system is often used in similar works.

Also, a usability analysis of the presented system on clinical populations of interest is an important future step to perform. In fact, this device is not as easily wearable as a smartwatch or an IMU (although being much smaller than RTK survey-grade devices).

Another possible future development is using a sensor fusion approach to integrate the functionality of the RTK-GPS receiver with an inertial sensor or other kinds of devices (Barry et al., 2018). This union could overcome the shortcomings of the GPS (the need to be used outdoors and the degradation of accuracy in situations with high interference). On the other hand, the information provided by the GPS, like true position and absolute time reference, could be beneficial for increasing an IMU functionality.

In conclusion, this is the first study that uses a mass-market RTK receiver to measure and validate WS in a real-world scenario to the best of our knowledge. The obtained results provide a preliminary insight and validation of the potential of a mass-market RTK receiver to measure walking speed in the real world. Notably, this work has proven the suitability of the simpleRTK2B for measuring average real-world walking speed even in environments with high interference and poor sky visibility. The measurements obtained in healthy adults were accurate enough to measure clinically important differences.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LR, LP, LC and SM conceived the idea and the rationale of this work. LR conducted and supervised the experimental sessions. LR and LP performed data analysis. LR and LP wrote the first draft of the manuscript that was iteratively improved by LC and SM.

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Internal Mechanisms of Human Motor Behaviour: A System-Theoretical Perspective

Wacław Petryński[1]*, Robert Staszkiewicz[2] and Mirosław Szyndera[3]

[1] Department of Tourism, Katowice Business University, Katowice, Poland, [2] Department of Physical Education and Sport, University of Physical Education, Kraków, Poland, [3] Department of Tourism and Recreation, University of Physical Education, Kraków, Poland

The authors present the conceptual and system-theoretical model of human motor behaviour. The main assumption is that movement is the only observable manifestation of all psychical processes, thus, it is the only phenomenon enabling the creation of hypotheses concerning the psychological conditioning of human behaviour. They pointed to the fact that in the field of biology, and all the more, in psychology, mathematical descriptions are hardly eligible. In this respect, a system-theoretical approach seems to be appropriate. The authors present two systems: information processing modalities in the human mind, based on Nikolai Bernstein's theory, and the series of processes from stimuli reception to motor response execution. Both these sub-systems make up a super-system. Its simplified graphical representation may be termed "Column Diagram." The authors analyse the functioning of this super-system in various intellectual-motor purposeful operations. The system-theoretical perspective enables clear categorisation of various human motor operations, their "driving" mechanisms, internal patterns, and their superficial physical and/or mathematical "appearance." The stream of consciousness in a human motor operation joins the various psychological constructs, which are reception, perception, attention, motivation, intellect, memory, etc., into one coherent, inseparable system.

Keywords: human motor operation, modalities' ladder, information processing in motor operation, mathematical description, system-theoretical description

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***Correspondence:**
Wacław Petryński
waclaw.petrynski@interia.pl

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INTRODUCTION

Since the seventeenth century, when Isaac Newton published his seminal work "*Philosophiae naturalis principia mathematica*" (Newton, 2018), only physics, attired in a mathematical skirt, became the main engine of the whole of science. In 1814 Pierre Simon de Laplace invented the all-knowing Laplace's Demon and wrote:

> *We ought then to regard the present state of the universe as the effect of its anterior state and as the cause of the one which is to follow. Given for one instant an intelligence which could comprehend all the forces by which nature is animated and the respective situation of the beings who compose it—an intelligence sufficiently vast to submit these data to analysis—it would embrace in the same formula the movements of the greatest bodies of the universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes* (de Laplace, 1902, p. 4).

The statement "*nothing would be uncertain*" sounds luscious, indeed, but nature is by far more complicated (and sometimes vicious). Nowadays it is clear to us that Laplace was too optimistic, and the "mathematical skeleton" of our world is not as hard as we wish it to be. The "mathematical engine" of science is very powerful, indeed, but it can drive only knowledge of a specific kind. It is highly effective in the non-living world, where the physical subjects passively obey the "stiff" laws external to them, which may be easily described mathematically. The items under investigation do not "actively" influence the relations joining them, and mathematical formalism makes very comfortable "rails for thinking," which release the scientist from arduous reasoning, while a given problem has been already described mathematically. This is why some of Albert Einstein's equations turned out to be "*wiser than Einstein himself*" (Coyne and Heller, 2008, p. 122).

However, the biological system not only passively obeys extrinsic physical laws but also actively shapes its relations with the environment. In biological organisms, and even structures, appear a new and important element: the intrinsic purposefulness, which actively influences the relations of the organism and the environment. Although the mechanisms of such shaping are relatively stable, developed during evolution, their mathematical description becomes hardly possible. This is why in the field of biology, the system approach has been invented by von Bertalanffy (1968).

The situation is still more complicated in psychology. In this case, the relations between an individual and the environment are shaped by at least three factors:

- Stiff physical laws, extrinsic to an individual;
- Somewhat elastic biological constraints developed for a given species during evolution; and quite fugacious psychological determinants, created uniquely by the individual.

Let us term the science on human motor behaviour "anthropokinetics." According to Ann VanSant, it comprises motor control, which works in the period of milliseconds; motor learning—in hours, days, weeks; and motor development—in months, years, decades (VanSant, 2003).

Nevertheless, only well-ordered knowledge deserves the noble title "science." In anthropokinetics, the promising perspective seems to be a system-theoretical approach (Petryński, 2016a). **Table 1** has been shown the system of sciences, which describes and enables the understanding of the process of motor behaviour creation and execution in living beings (especially in humans).

THE INSTRUMENTS FOR KNOWLEDGE ORDERING: MATHEMATICS AND SYSTEM

In three centuries, B.C., Euclid already remarked, *"the laws of nature are but the mathematical thoughts of God.*" Carl Friedrich Gauss declared mathematics the "*Queen of Sciences.*" One of the most eminent mathematicians in history, David Hilbert, stated:

> *Every kind of science, if it has only reached a certain degree of maturity, automatically becomes a part of mathematics.*

If this is true, then such a phenomenon marks a point, where the development of the "*kind of science*" starts to slow down. Because mathematics is not a fully universal instrument, enabling effective solving of every problem, but a science "from this point—to that point." It is useful, or even extremely useful, in the non-living world, where the physical bodies passively obey the laws extrinsic to them. While establishing a network of such laws and describing them mathematically, it becomes possible to precisely anticipate the behaviour of such bodies. The outstanding mathematician and physicist, Nobel Prize winner Roger Penrose, stated:

> *There are two other words I do not understand—*awareness *and* intelligence. *Well, why am I talking about things when I do not know what they mean? It is probably because I am a mathematician and mathematicians do not mind so much about that sort of thing. They do not need precise definitions of the things they are talking about, provided they can say something about the connections between them* (Penrose, 1997, p. 100).

Jim Holt quotes mathematician Alexander Grothendieck (Fields Medal laureate), who claimed that "*if you want to know the real nature of a mathematical object, don't look inside it but see how it plays with its peers*" (Holt, 2018, p. 86). Hence, mathematics deals merely with relations, and not with the essence of items under consideration. As goes the popular joke, "*An engineer thinks that his equations are an approximation to reality; a physicist thinks reality is an approximation to his equations; a mathematician does not care.*" Accordingly, in the sciences regarding living creatures, the statement by Hilbert may be paraphrased in such a form:

> *Every kind of science, if it only loses a hard ground of evident understandability and simple explainability under its feet* (e.g., *based on "new, original experimental data*"), *it automatically reaches for its lifebelt—mathematics.*

Unfortunately, such a lifebelt merely enables, in certain cases, passively drifting on the surface of knowledge, the understanding of which resides somewhere in the depth. Jack Cohen and Ian Stewart stated:

TABLE 1 | The system of sciences on motor behaviour of a human (Petryński, 2019, p. 29).

Task	"Actor"	Field	Sub-discipline	Discipline
Motor operation invention	Mind	Psychology	Anthropokinetics	
Motor operation control	Nervous system	Neurophysiology		Kinesiology
Motor operation execution	Musculoskeletal system	Physiology, anatomy	Biomechanics	
Operation results	Environment	Physics		

> *Mathematics wallows in emergent phenomena. It also came to terms, long ago, with something that often puzzles non-mathematicians. By definition, mathematical statements are tautologies. Their conclusions are logical consequences of their hypotheses. The hypotheses already "contain" the information in the conclusions. The conclusions add nothing to what was implicitly known already. Mathematics tells you nothing new* (Cohen and Stewart, 1994, p. 234).

Therefore, Michał Heller wrote:

> *For centuries we have worked out the empirical-mathematical method of world research. It is extremely efficacious, but for some price. It does not discern everything. Some things are transparent to it* (Heller, 2014, p. 295; transl. WP).

This statement includes, in fact, ominous content. The application of mathematics (or even sheer calculations) to issues where it is not eligible, may bring about disastrous results (O'Neil, 2016). Still earlier, in 1964, Garland Ashley published a paper entitled "*A declaration of independence from the statistical methods*" (Ashley, 1964). He remarked that statistics solves equations and not problems. In short, mathematics may produce models, whereas science (and practise, as well) needs, first of all, the interpretations. Summing up, it seems appropriate to quote the outstanding mathematician, Israel Moiseevich Gelfand, who also dealt with the biological issues:

> *There is only one thing that is more unreasonable than the unreasonable effectiveness of mathematics in physics, and this is the unreasonable ineffectiveness of mathematics in biology* (Borovik, 2018).

This is no doubt a bon mot, and as such, it cannot be a source of scientific knowledge. However, it may contain a scientific truth. As, Hugo Steinhaus remarked, "*a joke, which is only a joke, is not a joke*" (Steinhaus, 1980, p. 47). So, it must include a certain idea, sometimes even a deep one. Gelfand was not only one of the most outstanding mathematicians of the 20th century, but also quite closely cooperated with Nikolai Bernstein. At their first meeting, when Bernstein presented his ideas, Gelfand murmured: "Rubbish. . . *rubbish*. . .*rubbish*." But some years later, when he went along with Iosif Fejgenberg after Bernstein's funeral through the snowbound Moscow, he stated: "*We have just buried a great mathematician.*" Without a doubt, Bernstein's neurophysiological and evolutionary theory somehow influenced Gelfand's mathematical mind. So, his aphorism (dubbed by Mark Latash "Wigner-Gelfand principle") means that mathematics is not better than any other branch of science. It is highly, or even extremely efficient in some regions of knowledge, but not equally efficient beyond the kingdom of the Queen of Sciences. To apply it rationally in these "beyond regions," a scientist must realise, how its limitations are. They may result from the fact that mathematics is too "stiff" for biology.

This rule might be termed the "dictatorship of the equals sign." The same idea has been, slightly differently (and more concisely), expressed by Henri Poincaré, who stated that "*mathematics is the art of giving the same names to different things*." However, Aristotle had already remarked, "*the whole is greater than the sum of its parts.*" Unfortunately, in a mathematical equation there is no place for any "greater." On the contrary, a system is more elastic, and—first of all—it can produce a qualitatively new, unpredictable, emergent system effect (Morawski, 2005, p. 156; Petryński, 2016a, p. 6; Petryński, 2019, p. 24). As Lucien Cuénot stated, "*nothing is living in a cell but the whole cell*" (Gánti, 1986, p. 29; transl. WP). Therefore, in biology, the emergent system effect is life, and in psychology—the mind.

Incidentally, the term "emergent" means that—at least in motor control in humans—a system has a disposable structure. It consists of environment, body, mind, and task. After reaching its aim, it vanishes and leaves only a trace in memory termed "engram" (Semon, 1921). To solve next time a similar or even identical task, the performer has to build a new system. This makes a basis for what Bernstein termed "repetitions without repetitions." It makes one of the fundamentals of his theory, and at the same time made "bone of contention" between him and his great predecessors—Ivan Mikhaylovich Sechenov and Ivan Petrovich Pavlov.

In short, the whole of science is being built of interpretations. Mathematics yields some solutions, which in the non-living world may be identified with interpretations. Nevertheless, in a living world, solutions merely make up a basis for systemic interpretations. Mathematics may yield a "bare" solution, which creates only space for reasoning and interpretations. Nothing more. This is why we suggest looking at human behaviour from a systemic perspective, not so user-friendly and unambiguous like mathematics, indeed, yet by far more elastic.

Hence, mathematics can be used only for the superficial description of biological or psychological phenomena and processes, but it hardly contributes to their understanding. This may be exemplified with the "evidence-based assessment," which does not include any understanding; in fact, it vividly resembles the infamous behaviouristic "black box." It is devoid of understanding, which makes it a vital component of any theory. However, the science is being "woven" just of the theories. Accordingly, mathematics is not a "Queen of Sciences." To efficiently apply it in non-physical sciences, a scientist has to reject its royal robe, realise, what its limitations are, and not expect from it spectacular results in the fields, where it is able only to sweep given area of knowledge.

EVOLUTIONARY-NEUROPHYSIOLOGICAL SYSTEM: BERNSTEIN'S BRAIN SKYSCRAPER

Probably the most advanced systemic description of human motor capabilities, based on evolutionary and neurophysiological data, has been invented by Nikolai Aleksandrovich Bernstein, who was inspired by earlier works of John Hughlings Jackson (Jackson, 1884; Bernstein, 1947).

Iosif Moiseevich Feigenberg, Bernstein's friend and disciple, regarded movements as a key to understanding, how the brain works (Feigenberg, 2004, p. 44). Such a stance remains in proper accordance with this paper's motto, expressed by James Kalat (Kalat, 2007, p. 232). Unfortunately, the keyhole for observation is very small, whereas the item to be observed—is very extensive.

Thus, contemporary scientists rather remind the slaves from Plato's cave, and not the intellectual heroes, leading triumphantly whole humankind toward a better future.

Bernstein's system—which he termed "brain skyscrapers" (Bernstein, 1991, p. 121; Bernstein, 1996, p. 99)—has been presented in **Figure 1**. He invented such a model and described it in his main work, "*O postroyenii dvizheniy*" (*"On the construction of movements*") in 1947 (Bernstein, 1947), but he did not name it "*brain skyscraper.*" This term—very accurate in our opinion—appeared only in the book *"O lovkosti i yeyo rozvitii*" ("*On dexterity and its development*"), published in Russian in 1991, 25 years after Bernstein's death (Bernstein, 1991), and in English in 1996 (Bernstein, 1996). He wrote:

"*. . . it is true that the human brain is a multistoried building whose stories emerged successively, one after another."* (Bernstein, 1991, p. 121; Bernstein, 1996, p. 99; transl. Mark Latash).

However, the first full translation of Bernstein's "opus magnum," "On the construction of movements," appeared in English only in 2021 (Latash, 2021).

Incidentally, the perspective presented in **Figure 1** is systemic in its core, although Bernstein did not term it so, and Ludwig von Bertalanffy, considered to be the father of the theory of systems, published his seminal work only 20 years later (von Bertalanffy, 1968). Moreover, already in the 1960s, Paul MacLean developed the model of the "*triune brain*" (MacLean, 1990), similar to Bernstein's brain skyscraper, i.e., also of systemic nature.

It seems worth noting, too, that the "intellectual skeleton" of the "On the construction of movements," which has been published in 1947, is also cybernetic, though the seminal book of mathematician and philosopher Norbert Wiener, "*Cybernetics or control and communication in the animal and the machine,*" which marked the birth of cybernetics as a science, appeared only later, in 1948. Symptomatically, the formulation "*in an animal*" means that the origins of cybernetics are to be found—at least partly—in biology.

FUNCTIONAL SYSTEM: THE MODALITIES' LADDER

Because of the "Iron Curtain," Bernstein's achievements were not known in the West. The model by MacLean was regarded as "oversimplified" and "good enough for the layman." But was this right?

Let us take a by far simpler example. There is no doubt that for a car's movement the dynamics of fuel combustion in the cylinders are responsible. However, a good driver does not need to know its details: one needs only to know that for acceleration, one has to push the accelerator pedal. This remains in keeping—in general—with Bernstein's Degrees of Freedom Problem (Bernstein, 1947, p.) and Andy Clark's "*007 principles,*" which reads: "*to know only as much as you need to know to get the job done*" (Clark, 1989, p. 64).

In this context, the words of devil's prince Woland to Immanuel Kant in the famous novel "*Master and Margarita*" sound rather ominous:

As you will, Professor, but what you've thought up doesn't hang together. It's clever, maybe, but mighty unclear. You'll be laughed at (Bulgakov, 2008).

Therefore, one might say that very sophisticated theories are sometimes excellent, indeed, but they have no "cooperative power" with other theories. For example, the multidimensional theory of anxiety by Rainer Martens, Robin Vealey, and Damon Burton (Martens et al., 1990) probably reflects reality in more detail than the inverted U principle, but is in fact, too complicated to be commonly applicable. Consequently, the very applicability makes up an essential "passport to life" for each scientific theory.

Let us remember that the mind is a psychological "programming" being installed in the neurophysiological brain, which is equivalent to the "equipment." However, the "take-home message" from neurophysiology (brain skyscraper) reads: the more complex a motor action is, the higher (and slower) the region of the brain must be engaged. However, the whole system always works like one coherent unit. Accordingly, there is no "one-to-one" assignment of given motor action (or all the more, its component) to a specific "floor" of the brain skyscraper. In the final motor operation, it is not possible to discern, what results from perception, what from attention, what from intellect, etc.

However, in motor control and psychology, just the mind comprises the main point of interest. Accordingly, let us "cleanse" the brain skyscraper from evolutionary and neurophysiological components and "distil" only the information processing ones, while preserving the same (or nearly the same) system of relations. The result may be termed the "modalities' ladder" (Petryński, 2016a, 2019). To avoid misunderstandings, let us term the skyscraper's "floors"—"the levels," and the modalities' ladder's layers—"the rungs."

While assuming a functional perspective, it becomes necessary to make some small modifications. The A-level of the brain skyscraper must be divided in the modalities' ladder into two sub-rungs: A1, responsible for maintaining posture (basic muscle tonus), and A2, which controls strength production. Further, in the modalities ladder, there is no need to divide the C-level into C1 (agility) and C2 (dexterity) sub-levels. Accordingly, the ladder contains only one C-rung. A comparison of the brain skyscraper and the modalities ladder is shown in **Table 2**.

If it had one more column to the left, entitled "Neurophysiological structure of brain skyscraper," it would include neurophysiological information, which part of the central nervous system is mainly responsible for the content of the line in each of the four columns shown in **Table 2**. It would be consistent with the reductionist perspective, indeed, and would show, how learned the neurophysiologists are, but there is one important hitch. The system always works as one, coherent, and inseparable unit, and not as a sum of its components. Hence, its product is always an unpredictable, qualitatively, and new system effect. For example, the pallidum and thalamus play different roles in a fish, cat, and human. The division into components kills both the system and the system effects, whereas psychology and anthropokinetics, as well, deal exclusively with the system

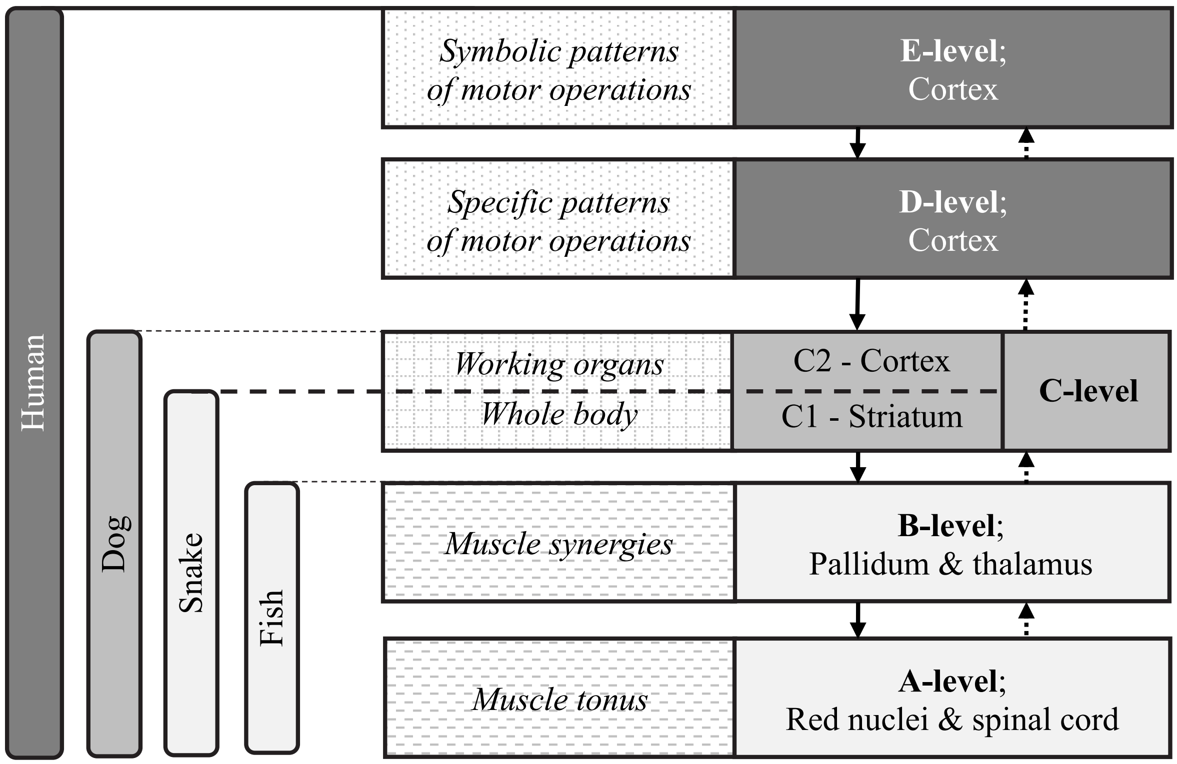

FIGURE 1 | The "brain skyscraper" according to N. A. Bernstein (Petryński, 2008, p. 166; Petryński, 2016a, p. 25, modified).

effects. A more detailed description of the brain skyscraper and the modalities' ladder can be found in Petryński (2016a, 2019).

- of motor operations—reflex, automatism, habit, performance;
- of their respective "driving mechanisms"—basic muscle tonus, strength control, technique, tactics (agility, dexterity), strategy and politics;
- of their "mental patterns"—coupling, template, scenario, programme, idea; and
- of their physical and mathematical "counterparts"—statics, dynamics, kinetics, kinematics, geometry, topology (**Table 2**).

In this context, one may admire the genius of Nikolai Bernstein. According to outstanding mathematician Stefan Banach, "*good mathematician sees analogies between theories, while the best of them discern analogies between analogies*" (Urbanek, 2014, p. 206). In motor control directly observable (and prone to experimental research) are only environmental stimuli and the resulting movement. Bernstein's great predecessors, Ivan Mikhaylovich Sechenov, and his follower, Nobel Prize winner Ivan Petrovich Pavlov, identified only one mechanism of movements control: the reflex (Sechenov, 1942; Pavlov, 1973). They did not analyse the possible various modalities in motor operation construction in living beings. On the other hand, Bernstein was able to catch a glimpse of "analogies between analogies," and discerned the deeply hidden multilevel and multimodal structure of the motor control mechanisms in humans.

In Bernstein's theory very important is the division of the "floors," active in each motor operation, into two groups: the main level and the background. The former works in the feedback mode (hence, it needs attention) and is responsible for what is being performed. The background works in the feedforward mode (it does not engage attention) and is responsible for how a given motor operation is being realised. Such a structure enables the efficient execution of complex operations, while making very frugal use of precious attention.

OPERATIONAL SYSTEM: THE STREAM OF CONSCIOUSNESS IN A MOTOR OPERATION

In a motor operation, with this term, we describe any purposeful motor action aimed at solving a specific task in the environment; the visible and measurable components are, exclusively, an initial stimulus (the releaser) and the effect of muscle activity (the biological strength), i.e., physical force and/or motion. Both phenomena make up the only "keyhole," through which we may peep on the action of the mind. Let us quote philosopher Andrzej Wohl: "*All that we dispose of, all that constitutes the resource of our culture, all the pieces of art, science and technology—all that results from motor activities...*" (Wohl, 1965, p. 5; transl. WP).

TABLE 2 | The comparison of the brain skyscraper and the modalities' ladder (Petryński, 2016a, p. 103; Petryński, 2019, p. 48).

BRAIN SKYSCRAPER; mental-motor abilities	**BASIC OPERATION; method of motor task solving**	**MODALITIES' LADDER; patterns of motor operations**	**THEORETICAL DESCRIPTION; "physical appearance" of the movement**
E-level, fantastic image of reality, FANTASY	No motor operation, POLITICS (wisdom, anticipation)	E-rung symbolic modality IDEA	Topology
D-level, accurate representation of reality, COMMON SENSE	Performance, STRATEGY effectiveness of action	D-rung verbal modality PROGRAMME	Geometry
C2-sublevel, net of muscle synergies, working organs, DEXTERITY C1-sublevel, net of muscle synergies, whole body, AGILITY	Habit, TACTICS (measure-in-eye)	C-rung remote (teleceptive) modality SCENARIO	Kinematics
B-level, two muscles' synergy, MOVEMENTS' HARMONY	Automatism, TECHNIQUE (movement smartness)	B-rung Contactceptive modality TEMPLATE	Kinetics
A-level, single muscle contraction STRENGTH,	Reflex, STRENGTH CONTROL (feeling-in-hand)	A2-subrung proprioceptive modality COUPLING	Dynamics
MUSCLE TONUS, (background of all backgrounds)	MAINTAINING POSTURE (feeling of one's body position)	A1-subrung kinaesthetic modality KINAESTHESIA	Statics

Let us emphasise that there are no other behaviours than motor ones because movement is the only method of manifestation of what is going on in the mind and the only method of influencing the environment by a human as well. Even if only that of the lips and tongue.

What goes on between reception of the releaser and production of movement we can only conjecture, for these phenomena and processes cannot be researched directly and experimentally. It seems worth bearing in mind that at the brink of the nineteenth and twentieth century, and in the following decades as well, a very strong impulse for the development of physics was the purely theoretical, "crazy" works of Max Planck, Albert Einstein, Niels Bohr, Peter Higgs, and many others. Respective experiments, in which the phenomena congruent with theoretical anticipation were observed, had been performed much later. For example, the apparent moonshine concepts, like the general theory of relativity, waited for such an experiment 4 years; the Higgs boson in half a century and the gravitational waves in full century. Let us add that the matter of human motor behaviour is, by far, more complex than any problem in physics. Hence, the expectation of immediate experimental verifiability of hypotheses prevents scientists from the free formulation of conjectures, being the most primeval "seeds" of science. In this respect, a highly instructive sound of words of Nobel Prize winner Niels Bohr to another Nobelist, Wolfgang Pauli: "*We are all agreed that your theory is crazy. The question, which divides us, is whether it is crazy enough to have a chance of being correct. My own feeling is that it is not crazy enough*." It is hard to resist the impression that nowadays, the non-mathematical biology, psychology, and science on motor behaviour need just crazy ideas more than "*commonly accepted methodologies*" and computers.

By the way: the theory, being the subject of the comment of Niels Bohr, cannot count among the greatest achievements of Wolfgang Pauli and of the co-author of this concept, another Nobelist, Werner Heisenberg.

Nevertheless, self-censorship strongly inhibits the development of anthropokinetics. To publish a scientific paper ("*publish or perish*"), it must be built in agreement with the template: material—research—discussion—conclusion. Such a template promotes the "*scientists with noses in the ground*." It is enough to adequately collect many results of experiments, to process them with what may be termed "*kitchen statistics*" (or any other "*commonly accepted methodology*"), then to name the results with the word "*conclusions*" (it is an evident, yet very popular humbug)—and so, to build one's position in science. Unfortunately, such works do not contribute to progress in science (with the capital "S"). Nevertheless, such papers comprise the majority of the content of scientific journals and magazines. Jack Cohen and Ian Stewart wrote:

> *At least 999 out of a thousand scientific papers are about complex details, but the one that we treasure and for which we award a Nobel Prize is the one that reveals a new simplicity. It is as if simplicities are all around us but scattered rather thinly. Some scientists are rather good at laying hands on them; they must have the right kind of mind, seeing the world with unusual clarity. Albert Einstein specialized in big simplicities, and so did Paul Dirac, Gregor Mendel, and Dimitri Mendeleev (Cohen and Stewart, 1994, p. 231).*

In this statement, one may identify the word "*simplicity*" with the term "*theory,*" because "*a theory is a kind of code that transforms complicated messages from nature into much simpler ones*" (Cohen and Stewart, 1994, p. 363). For, as it has been said, there is no direct experimental access to the series of phenomena and processes from the releaser to the visible motor response, let us try to build a conceptual cause-effect chain that joins both these events. While borrowing the term from William James, let us name it "stream of consciousness." It has to be placed in the sphere of theory, i.e., in the natural environment of science. Let us emphasise that it is not possible to build such a chain while basing on "tangible" experiments. In this context rather ominously sound the words by Henry Mencken, who noticed that "*science, at the bottom, is anti-intellectual; it always distrusts pure reason and demands the production of objective fact.*"

The structure of a sensorimotor response has been described in detail by Richard Schmidt (Schmidt, 1988, p. 65). He divided it into three periods: foreperiod (FP), reaction time (RT), and motor time (MT). The RT and MT together, make up the response time (RPT).

The FP commences with the reception of a signal, i.e., a stimulus which foreruns another stimulus. The latter may initiate a motor response. Let us term it "releaser."

The RT starts with the reception of the releaser, but there is not yet any electrical activity in the muscles; it ends when the MT starts, i.e., the movement gets observable.

The term MT denotes a period when the movement (or purposeful motionlessness, as, e.g., in targeting) becomes visible. It is over along with the termination of the movement.

In such a model, the RT is the main period, when the abstract pattern of a motor response may be shaped. The conceptual information processing cause-effect chain in a sensorimotor response—the stream of consciousness, cannot be directly observed experimentally.

The first link of the chain is stimulus **reception**. It is not "understandable" to the central nervous system but arouses sense organs. In turn, they produce neural sensory inputs, of electrical nature. They are "understandable" for the neural system and may stimulate it. This link produces awareness.

The second link is **perception**, i.e., assigning the information retrieved from memory to the specific sensory input. Thus, it creates chunks of information. This link produces consciousness.

The third link is **attention**, which, based on previous experiences, assigns specific "weight" to each chunk of information and creates their hierarchy. The most important ones make the "fuel" for further information processing. The insufficiently important are rejected and forgotten; they are not transmitted further to motivation and intellect and do not charge them.

The fourth link, **motivation**, is a "doorkeeper" to the intellect. It transmits (or not) the most important chunks of information and determines the intensity of their further processing.

The fifth link, **intellect**, makes up a specific apex in the whole chain. It is a final link of the "ascending path" (more and more abstract, less and fewer information chunks to be processed, "the preparatory sub-system"), and at the same time, the initial link of the "descending path" (less and less abstract, more and more information patterns, "the executive sub-system"). It creates an abstract pattern of the whole possible motor operation. The conceptual structure of the intellect consists of three components: intelligence, intuition, and instinct.

Intelligence comprises the "armed forces" of intellect and is responsible for the final assembly of a motor operation pattern. It needs the full information necessary to solve a given task.

Usually, an individual does not dispose of full information. **Intuition** is responsible for guessing the lacking information (right or wrong).

Instinct directs the search of information toward those regions of memory, where its discovery is most probable (Petryński, 2016a,b; Petryński, 2019).

Until this link is formed, the whole chain deals with "bare" information. Intellect produces organised, purposeful patterns, which are processed in further links.

The sixth link, **foresight**, assesses, on the base of earlier experience, the applicability of the pattern worked out by the intellect. On the descending path, it is somehow "symmetrical" to attention, which resides on the ascending path.

The seventh link, **decision**, finally transfers the motor operation pattern into execution (or not); so, it is "symmetrical" to motivation.

In the eight link, **skills**, already existing patterns (or component sub-patterns) of the motor operation are being retrieved.

The **efferent copies** make up the ninth link of the chain. They are motor operation patterns recorded in memory and enhance the execution of a similar motor operation in the future.

Finally, the tenth link in the **production of strength and movement** by the muscles, bringing about desirable effects in an environment (**Table 3**).

While looking at **Figure 2**, one may learn that from perception to intellect, the system deals with more or less "bare" information, whereas from intellect to efferent copies—with organised patterns, i.e., the systems of deliberately organised information.

Incidentally: The sensorimotor response pattern by Schmidt shows, how important the ability to anticipate is, which first appeared at the C-level of the brain skyscraper. It makes the crucial factor in the merciless, evolutionary struggle for life. It enables translation of the process of preparation of the motor response pattern ahead of the moment of the reception of the releaser. Such a process "resides" in the foreperiod (FP), which commences with the reception of a signal, which foreruns the releaser. Only the latter may launch the whole stream of consciousness resulting in a final motor operation. Thus, in the presence of a signal, the RT is reduced to near nil. Moreover, the MT may even start before the reception of the releaser, based only on anticipation.

JOINED FUNCTIONAL AND OPERATIONAL SYSTEMS: COLUMN DIAGRAM

The modalities' ladder and the motor response chain are simple enough to be joined and create another system, which may be termed "Column Diagram" (CD, **Figure 2**). Its idea is that the motor response chain may work at each rung of the modalities'

TABLE 3 | The links of conceptual motor response information processing.

No.	Input	Link	Product
1.	Stimuli	*Reception*	Sensory inputs
2.	Sensory inputs	*Perception*	Chunks of information
3.	Chunks of information	*Attention*	Essential information
4.	Essential information	*Motivation*	Operational information
5.	Operational information	*Intellect*	Possible operation pattern
6.	Possible operation pattern	*Foresight*	Realisable operation pattern
7.	Realisable operation pattern	*Decision*	Executable operation pattern
8.	Executable operation pattern	*Skills*	Motor commands pattern
9.	Motor commands pattern	*Efferent copies*	Pattern recording
10.	Motor commands pattern	*Muscles*	Strength, movement

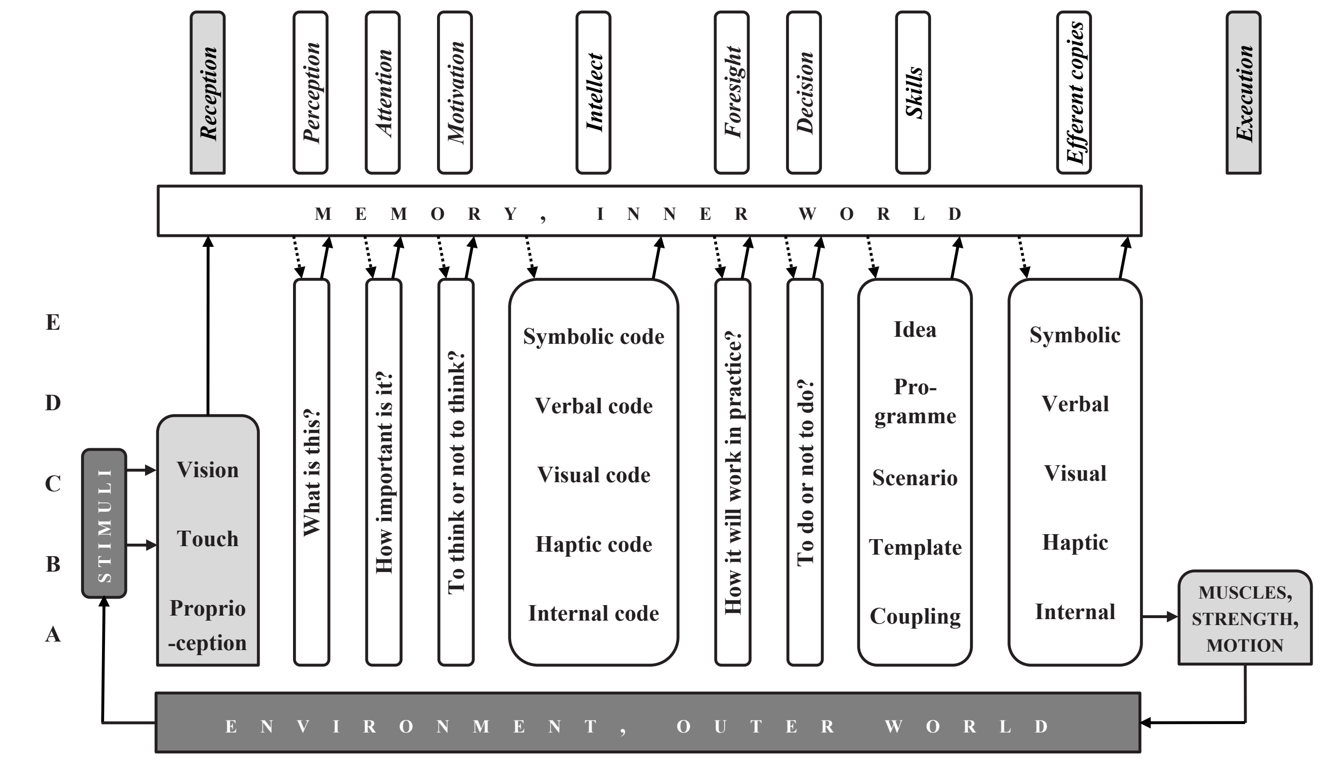

FIGURE 2 | Column Diagram" of information processing in a sensorimotor response. Dark blocks, physics; light grey blocks, physiology; white blocks, psychology.

ladder, while taking into account the specificity of information processing at a given rung. For example, the time perception "able to work," being the base for anticipation, appeared only at C-level. Consequently, in the modalities' ladder intuition cannot work at rungs lower than C, though a specific motor operation pattern may be prepared at C- or even D- level, and then "pushed down" for execution to B-level.

The CD, just like the stream of consciousness, may be divided into two parts: from reception to intellect (the "preparatory sub-system," from past to present, **Figure 3**) and from intellect to execution (the "executive sub-system," from present to future, **Figure 4**). Symptomatically, intellect, memory, and environment are components of both.

Let us look more closely at the column "Skills."

The abstract, internal patterns result in practise with specific motor operations: reflexes at A-rung, automatisms at B-rung, habits at C-rung, and performances at D-rung. E-rung does not have its "own" motor operations.

Apropos: This issue created the main "bone of contention" between two Giants: Ivan Petrovich Pavlov and Nikolai Aleksandrovich Bernstein. According to Pavlov, each motor operation may consist of a shorter or longer chain of simple reflexes. On the other hand, Bernstein regarded that particular motor operations do not differ from one another only quantitatively (lower or higher number of reflexes), but qualitatively (various modalities of information underlying a given motor operation). Also, in by far simpler mathematics, it is not possible to solve a complex differential equation with the plain multiplication table alone.

The CD (**Figures 2–4**) show all the possible chains of information processing. In fact, according to the Degrees of Freedom Reduction rule, in a specific motor operation, only the necessary rungs are active. The C-rung operation (e.g., cycling) is shown in **Figure 5**, and the E-rung operation (e.g., theory creation) is in **Figure 6**. In the latter, the motor components are reduced to near nil (they are not essential). Both these figures may be interpreted as specific illustrations of Bernstein's "*Degrees of Freedom Reduction rule*" or Clark's "*007 principles.*"

Incidentally, the D-rung makes a "seat" of common sense. So, while looking at **Figure 6**, one might discover, why an ingenious scientist, who is intensively working intellectually, can look at an egg and boil a wristwatch.

It is worth emphasising that the assumption that information processing works at all five rungs of the modalities' ladder makes the notion of "subconsciousness" superfluous (Petryński, 2016b). For the coining of this term often Sigmund Freud is being credited. However, he wrote:

> *I should also like to hear you admit that our designations—* unconscious, fore-conscious, *and* conscious *are much less likely to arouse prejudice, and are easier to justify than others that have been used or suggested—such as* sub-conscious, inter-conscious, between-conscious, *etc.* (Freud, 1920, p. 257).

In ML's perspective, the difference between "sub-" and "fore-consciousness" is fundamental. The former concerns different modalities of the consciousness, whereas the latter concerns the various intensities of the consciousness of the same modality.

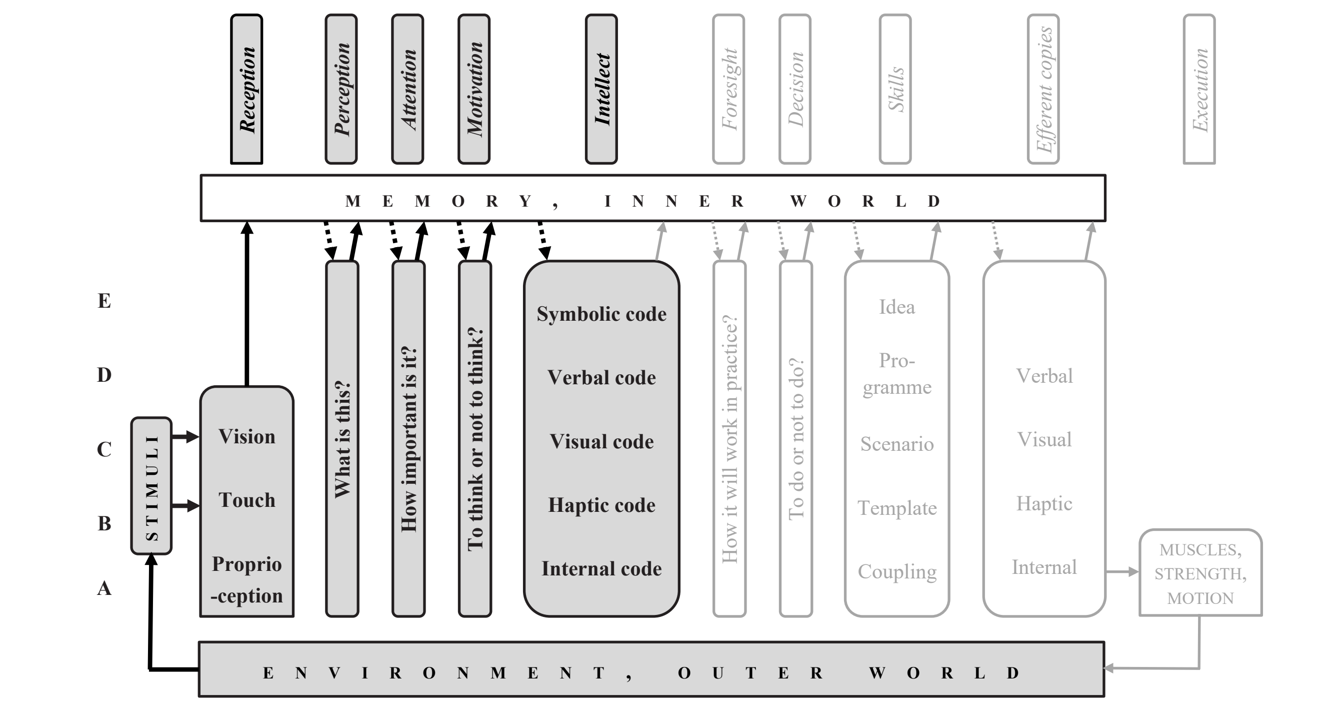

FIGURE 3 | "Column diagram"; human motor operation, the preparatory path.

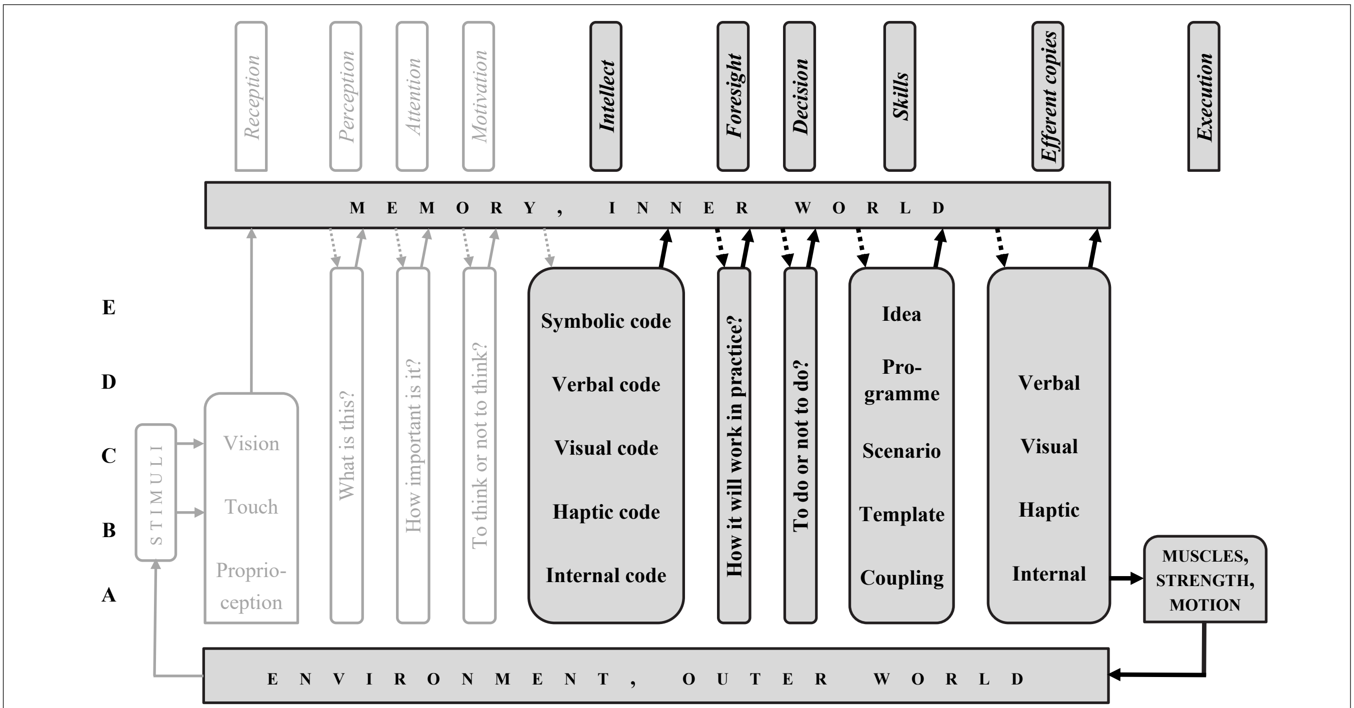

FIGURE 4 | "Column diagram"; human motor operation, the executive path.

To sum up, it seems worth emphasising a very important difference between a mathematical equation and a system. The former makes a kind of universal "stiff rails" for solutions with many different sets of data. For example, the same equation may be applied to both hydraulic and electrical issues (electronic-hydraulic analogy). The same equation describes the

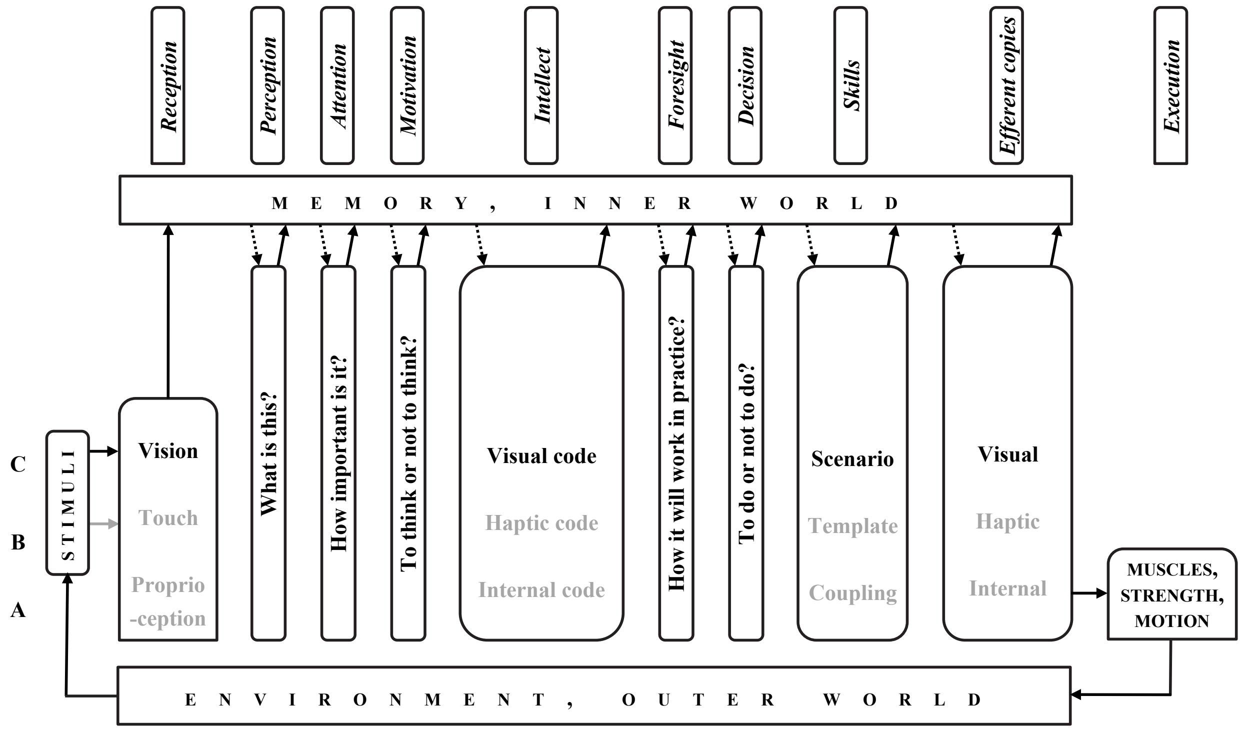

FIGURE 5 | Information processing while cycling. The A- and B-rung work "in the background," i.e., without attention focusing.

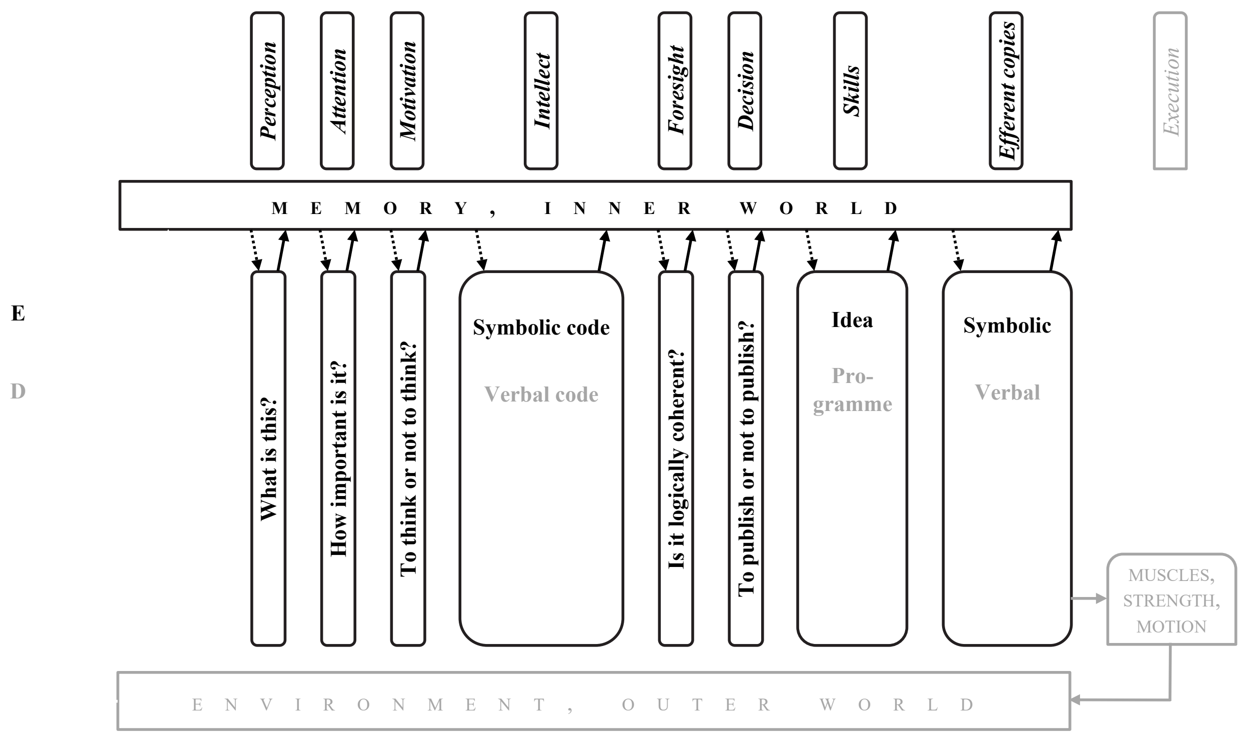

FIGURE 6 | Information processing while creating an abstract mathematical construct. Even if mainly the E-rung works, the movement at A-rung is necessary to transfer the results of processing to the environment.

distribution of tension in a bar in torsion and deformation of an elastic membrane under pressure (membrane analogy by Ludwig Prandtl). On the other hand, an anthropokinetic system is a disposable structure consisting of environment, body, mind, and a task to be solved with the motion. Thus, the pallidum and thalamus play different functions in the "motor creation system" not only in a fish and in a human, but also the same living being in different motor operations.

GENERAL DISCUSSION: MATHEMATICS AND SYSTEM-THEORETICAL APPROACH

Mathematician René Thom stated that contemporary science became possible only in the 17th century, when the theory got ahead of the experiment (Sorman, 1993, p. 61). Without doubt, he thought about physics; it got then very hard, mathematical fundamentals, which enabled its eventful development and progress. Incontestable, a breakthrough was the creation of differential calculus by Isaac Newton and Gottfried Leibniz. This key moment may be regarded as the birth of "full-blooded" mathematics, as opposed to sheer calculations. It was a turning point that commenced the triumphant marsh of mathematics, not only in physics, but in whole contemporary (then) science.

However, as early as the fifteenth century, in the era of "sheer calculations," Leonardo da Vinci remarked that "*there is no certainty in sciences where one of the mathematical sciences cannot be applied, or which are not in relation with these mathematics*" (Gauss, 2021). Nearly five centuries later, in the era of "full-blooded mathematics," philosopher and mathematician Bertrand Russel stated that "*mathematics may be defined as the subject, in which we do not know what we are talking about, nor whether what we are saying is true.*" (Russell, 2004, p. 58). Mathematician Israel Gelfand formulated the already cited "Wigner-Gelfand principle." Biologist Jack Cohen and mathematician Ian Stewart wrote:

> *By definition, all mathematical statements are tautologies. Their conclusions are logical consequences of their hypotheses. The hypotheses already "contain" the information in the conclusions. The conclusions add nothing to what was implicitly known already. Mathematics tells you nothing new* (Cohen and Stewart, 1994, p. 234).

Philosopher and physicist, Michał Heller, remarked:

> *One might assume that the simplicity of mathematical structures, with which we are modelling the world, are so different from the richness of the real structure of the world that instead of similarity we should speak rather about a resonance, which happens between the structure of the world and the structure of its mathematical models created by us* (Heller, 2011, p. 58; transl. WP).

Accordingly, mathematics sees only the aspects of reality remaining in Heller's resonance, whereas the other ones are transparent to it. The explanation of such a phenomenon one might find in the statements of Roger Penrose and Alexander Grothendieck that mathematics is interested only in the relations between items under consideration, and not in their very nature. This is highly effective in the non-living world, where physical bodies have none of their own "personalities" and passively obey the physical laws, extrinsic to them. In this field, elegant and user-friendly mathematics makes an excellent instrument for quitely easy and precise scientific descriptions. Unfortunately, "*Physics deals with an invented, simplified world. This is how it derives its strength; this is why it works so well: Its raw material is of a type that can be placed in simple settings. Sciences like biology are less fortunate*" (Cohen and Stewart, 1994, p. 12).

As an additional comment concerning mathematics, let us quote the statement by Jack Cohen and Ian Stewart that "*a Theory of Everything would have the whole universe wrapped up; and that's precisely what would make it useless*" (Cohen and Stewart, 1994, p. 365). Another formulation of the same in fact idea has been expressed by mathematician John Barrow, who stated that "*[...] paradoxically, science is only possible because some things are impossible*" (Barrow, 1999, p. vii).

In this respect, highly and instructively sound statements of Nobelist-physicist, Niels Bohr and Erwin Schrödinger. The former wrote:

> *"[...] the existence of life must be considered as an elementary fact that cannot be explained but must be taken as a starting point in biology, in a similar way as the quantum of action, which appears as an irrational element from the point of view of classical mechanical physics, taken together with the existence of elementary particles, forms the foundation of atomic physics. The asserted impossibility of a physical or chemical explanation of the function peculiar to life would in this sense be analogous to the insufficiency of the mechanical analysis for the understanding of the stability of atoms."* (Bohr, 1933, p. 458).

Nearly 20 years later Erwin Schrödinger wrote:

> *Today, thanks to the ingenious work of biologists, mainly of geneticists, during the last thirty or 40 years, enough is known about the actual material structure of organisms and about their functioning to state that, and to tell precisely why, present-day physics and chemistry could not possibly account for what happens in space and time within a living organism* (Schrödinger, 2013, p. 4).

Incidentally, the same fact idea one might find in the famous "Faust" by Johann Wolfgang Goethe, who wrote it at the beginning of the nineteenth century:

> *To know and note the living, you'll find it.*
> *Best to first dispense with the spirit:*
> *Then with the pieces in your hand,*
> *Ah! You've only lost the spiritual bond.*
> *"Natural treatment," Chemistry calls it.*
> *Mocks at herself and does know it* (Goethe, 2003, p. 79).

About half of the twentieth century also biologist Lucien Cuénot stated that "*in a cell, there is nothing living, but the cell itself.*" Why biology, and—even more—psychology cannot be easily "harnessed" with mathematical formalism? Probably because, unlike the physical bodies, living organisms are endowed with a kind of psychology and do not only passively obey the extrinsic physical laws, but also actively shape their relations to reality. In biology one has to do with the intrinsic purposefulness – quite "stiff", formed in the course of evolution. On the other hand, in psychology, the intrinsic intentionality has been already developed. It is rather fugacious and shaped at a given moment by an individual. Mathematics may be useful in the description of superficial phenomena, in ordering observations. However, it is hardly useful in discovering the very nature of items under consideration in biology and psychology. Michał Heller remarked that "*the science sees the world through theories*" (Heller, 2011, p. 4; transl. WP). One might paraphrase this statement and say that "*mathematics sees the world through relations.*" However, in living beings, their "relations to peers" result to a great extent from their inner biological and psychological structure, which seems to remain, at least at the contemporary state of science development, beyond the borders of the kingdom of "Queen of Sciences."

In such a situation the promising instrument for ordering the knowledge in both these areas seems to be the theory of systems. As opposed to a mathematical equation, the system can create a qualitatively new, unpredictable system effect. Another important difference as compared to the mathematical equation is that a system is a one-off mechanism for problem solving and to solve another similar or even the same problem, it is necessary to build a system anew. On the other hand, the mathematical equation makes it rather stiff, very convenient for scientists "rails for thinking," which may be used many times without any alterations.

To sum up, in the area of unknown, where resides the intellectual chaos, scientists believe, not know, that it is deterministic. This conviction has been expressed by Pierre Simon de Laplace, when he created his famous "demon"; just this belief made the very fundamental of Einstein's image of science. The unknown is being penetrated at first by philosophy, which strives to "harness" the incomprehensible world with a kind of logic. However, to become a science, this provisionally structured, yet (deterministically, hopefully) chaotic knowledge, must be properly ordered. The basic instruments for this process may be, roughly, either the "stiff" mathematics or the "elastic" system. Our thesis reads that the latter is at least not less effective than the former. Moreover, we claim that in biology, psychology, and anthropokinetics, it has a clear advantage over the "Queen of Sciences." Therefore, we strived to present the issues of motor human behaviour from the system-theoretical perspective.

CONCLUSION

The modalities' ladder and the stream of consciousness in a motor operation are the systems somehow "orthogonal" to each other. However, they may be linked together to form what has been shown in this paper as a column diagram. The more detailed analysis of the structure built of both these systems together, along with a blueprint of a human motor operation, more detailed than a CD, termed "movements' management matrix" (MMM), can be found in Petryński (2016a, p. 133) and Petryński (2019, p. 71).

It must be emphasised that both these systems are of non-linear nature. The links between particular elements of the stream of consciousness are non-linear; for example, attention transfers to motivation the information, which is "filtered" and selectively reinforced (or suppressed). The same concerns the rungs of the modalities' ladder. Here the non-linearity emerges as incomplete "translatability" of information code specific to one rung into the "language" (proprioceptive, contactceptive, teleceptive, verbal, or symbolic) specific to a neighbouring rung. In this case, we have to do with a specific kind of the "epistemological obstacle," as by Gaston Bachelard (Bachelard, 2002, p. 24). However, in this respect, such an "obstacle" has a great creative power in the abstract field of intellect. Incidentally, probably, just the non-linearity makes the main fundamental for the most important product of a system: the emergent, qualitatively new, and unpredictable system effect.

In fact, only this issue has made the main bone of contention between Pavlov and Bernstein. Great Ivan saw the simple reflex as the only mechanism "driving" any motor activity, whereas Great Nikolai discerned various modalities, non-linearly joined with each other, in different motor operations. As a result, he has built a specific "gearbox," which is the "brain skyscraper," thus, enabling selection of optimal modality of information processing for a given motor operation.

The system-theoretical perspective enables clear arrangement of the sciences' underlying issues of human motor behaviour: psychology and neurophysiology (anthropokinetics), as well as physiology, anatomy, and physics (biomechanics). Together, they make the components of the more general kinesiology.

The concept of modalities' ladder, firmly rooted in Bernstein's theory, enables clear categorisation of motor operations, their psychological "driving mechanisms," their internal mental patterns, as well as their physical and mathematical "counterparts."

The practitioners RS and MS found such categorisations useful in their didactical activity. In a motor performance (D-rung), main load burdens the mental sphere, whereas the C- (habits), B- (automatisms), and A- (reflexes) rungs make merely the "armed forces" of a motor operation. The most advanced of such an operation, where the motor element prevails, is no doubt the habit. It makes a system (not a sheer sum!) of automatisms and reflexes, which in the habit should work in feedforward mode, i.e., without attention engagement. This, alone, makes the whole structure reasonable. Symptomatically, as a system, the habit always works as a coherent and inseparable unit. As such, it should be performed by a learner fluently and efficiently. However, a teacher should discern the "critical points" of the habit, which are automatisms and reflexes, and to correct just those elements, which determine the quality of a whole habit. In this respect, the crucial is identification of particular sub-operations in a habit by a teacher.

The concept of stream of consciousness joins the particular links of the cause-effect chain—reception, perception, attention etc.—in information processing during a motor operation in one coherent series. It always works as an inseparable system. Hence, in the result it is not possible to determine (or even evaluate), which part of the resulting motor operation origins in attention, which in intelligence, and which in foresight. Consequently, purely experimental, yet valuable, research of these issues, e.g., by simple calculation of the value of IQ, seems hardly possible.

Moreover, a detailed analysis of these psychological mechanisms makes no sense separately at all! For example, while seen from system-theoretical perspective, memory of such gains will have meaning only when it gets included into a system consisting of environment, task, body, mind, and solution. Such a system is a one-time construct. To perform, once more, a similar or even identical motor operation, one has to build a new system. For example, if a driver has to go with his/her car from point A to point B, the elements of a system are: point A, car, driver and point B. However, when s/he goes back, we have to do with a new system: point B, car, driver, and point A. Therefore, the rule "repetitions without repetitions" makes one of the fundamentals (if not the main one) of Nikolai Bernstein's theory. Probably, earlier foreknew this Sigmund Freud, who opposed to experimental research in psychology. As Tomasz Witkowski remarked, he thought that "*those phenomena are so elusive and delicate that it is possible to discern them only in the clinical interview, and not in an experimental research, which needs some level of standardization*" (Witkowski, 2015, p. 181; transl. WP). Let us emphasise, once more, that the systemic nature of a motor operation, along with its abstract mental pattern, seems to be hardly researchable experimentally. To perform this with any success (possible to achieve at all), a scientist must realise, what are the limitations of experimental research in this field.

Once more, it should be pointed up that mathematics, although elegant, fashionable, and user friendly, is far from being fully universal. Moreover, nowadays, the full of fantasy, smiling, and intellectually provoking Miss Mathematics, is being substituted with boring (yet reliable) Miss Calculations. The instant and zero-one sheer (if not primitive) operations in computers kill the full of fantasy and understanding mathematical analysis. In this respect, highly symptomatic is the "halting problem." This term, roughly means that after launching a computer procedure, the scientist loses any control over it until the "number cruncher" expels the solution; solution, but not understanding. While paraphrasing mathematician Hugo Steinhaus, "*due to dissemination of computer technology, nowadays it became possible to conduct research, publish papers and achieve scientific degrees and titles while still being an illiterate*" (Steinhaus, 1980, p. 56; transl. WP). It seems worth noting that Steinhaus passed away in 1972, and the explosion of computer technology came only later.

It seems appropriate to quote another mathematician, Israel Moiseevich Gelfand, who stated that: "*Application of contemporary mathematics and physics to biology is a dead-end. . . Do not waste time on mathematics—think!*" (Latash, 2008, p. 56).

In that context, in the field of biology and psychology, the systemic approach seems to be a method of investigation far more eligible than mathematics. By now it does not produce the quantitative solutions of the issues under examination, indeed. However, mathematics (and, all the more, calculations) was not able to create a qualitative image of psychological phenomena and processes. In short, contemporary science cannot create a precise representation, like a technical drawing, of psychological phenomena. Nevertheless, scientists should strive to produce at least an impressionistic (and holistic) image of those issues, describing not their details, but their "soul." Within this context, the system-theoretical approach seems to be promising.

The presented work is no doubts a speculative one. However, it concerns the regions of human knowledge (and science as well) accessible only by speculations. Even Richard Dawkins, known of his repartee, stated, rather timidly: "*careful inference can be more reliable than "actual observation," however strongly our intuition protests at admitting it.*" (de Laplace, 1902, p. 15). "Rather timidly," because some regions of science are cognisable only by "careful inference"; there is no direct experimental contact to them. In the CD directly observable are only the stimuli and the motion; all intermediate links of the stream of consciousness are accessible only by "careful inference." The same concerns particular rungs of the modalities' ladder. However, let us remember that in physics general theory of relativity, Higgs boson and gravitational waves must wait for "their" experiments for four, fifty, and hundred years, respectively. Moreover, the biological, psychological, and anthropokinetics issues are, by far, more complicated the physical ones. "Very symptomatic" is also the already cited statement by Michał Heller: "*science sees the world through theories.*" Concluding in this context, highly instructive readings of the aphorism by George B. Shaw: "*The reasonable man adapts himself to the world; the unreasonable man persists in trying to adapt the world to himself. Therefore, all progress depends on the unreasonable man.*"

AUTHOR CONTRIBUTIONS

WP, RS, and MS contributed to conception and design of the study. WP organised the database and wrote the first draft of the manuscript. RS and MS completed fragments and wrote corrections of first version. All authors contributed to manuscript revision, read, and approved the submitted version.

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Impact of Motor-Cognitive Interventions on Selected Gait and Balance Outcomes in Older Adults: A Systematic Review and Meta-Analysis of Randomized Controlled Trials

Kaja Teraz[1,2], Luka Šlosar[1], Armin H. Paravlić[1,2,3], Eling D. de Bruin[4,5] and Uros Marusic[1,6]*

[1] Institute for Kinesiology Research, Science and Research Centre Koper, Koper, Slovenia, [2] Faculty of Sport, University of Ljubljana, Ljubljana, Slovenia, [3] Faculty of Sports Studies, Masaryk University, Brno, Czechia, [4] Institute of Human Movement Sciences and Sport, Department of Health Sciences and Technology, ETH Zurich, Zurich, Switzerland, [5] Division of Physiotherapy, Department of Neurobiology, Care Sciences and Society, Karolinska Institute, Stockholm, Sweden, [6] Department of Health Sciences, Alma Mater Europaea – ECM, Maribor, Slovenia

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University of Castilla-La Mancha, Spain

***Correspondence:**
Eling D. de Bruin
eling.debruin@hest.ethz.ch

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Background: Efficient performance of most daily activities requires intact and simultaneous execution of motor and cognitive tasks. To mitigate age-related functional decline, various combinations of motor and cognitive training have shown promising results. The aim of this systematic review and meta-analysis of randomized controlled trials (RCTs) was to evaluate the efficacy of different types of motor-cognitive training interventions (e.g., sequential and simultaneous) on selected functional outcomes in healthy older adults.

Methods: Six online academic databases were used to retrieve eligible RCTs up to April 2021, following PRISMA guidelines and PICO criteria. A random-effects model was used for all meta-analyses conducted on selected functional outcomes: single- and dual-task gait speed, the Timed Up and Go Test (TUG), and Berg Balance Scale (BBS) score. Effect size (ES) was calculated as Hedges' g and interpreted as: *trivial*: <0.20, *small*: 0.20–0.60, *moderate*: 0.61–1.20, *large:* 1.21–2.00, *very large*: 2.01–4.00 or *extremely large* >4.00.

Results: From 2,546 retrieved records, 91 RCTs were included for meta-analysis (n = 3,745 participants; 64.7–86.9 years). The motor-cognitive interventions included differed according to the type of training (e.g., sequential, simultaneous with additional cognitive task or exergame training. The results showed that motor-cognitive interventions can improve gait speed under single-task conditions (*small* ES = 0.34, P = 0.003). The effect of the intervention was moderated by the type of control group (Q = 6.203, P = 0.013): passive (*moderate* ES = 0.941, P = 0.001) vs. active controls (*trivial* ES = 0.153, P = 0.180). No significant effect was found for dual-task walking outcomes (P = 0.063). Motor-cognitive intervention had a positive effect on TUG (*small* ES = 0.42, P < 0.001), where the effect of intervention was moderated by control group [passive (*moderate* ES = 0.73, P = 0.001) vs. active (*small* ES = 0.20, P = 0.020)], but not by the type of training ($P = 0.064$). Finally, BBS scores were positively affected by motor-cognitive interventions (*small* ES = 0.59, $P < 0.001$) with however no significant differences between type of control group ($P = 0.529$) or intervention modality ($P = 0.585$).

Conclusions: This study provides evidence for the effectiveness of various types of motor-cognitive interventions on performance-based measures of functional mobility in healthy older adults. With respect to significant effects, gait speed under single-task condition was improved by motor-cognitive interventions, but the evidence shows that this type of intervention is not necessarily more beneficial than motor training alone. On the other hand, motor-cognitive interventions are better at improving multicomponent tasks of dynamic balance and mobility function, as measured by the TUG. Because of substantial heterogeneity and the current limited availability of different types of interventions, the conclusions should be interpreted with caution.

Keywords: motor-cognitive intervention, dual-task, elderly, mobility, postural control

INTRODUCTION

Aging leads to a decline in physical and cognitive abilities, which has been associated with an increased incidence of falls (Lord et al., 1999; Masud and Robert, 2001; Ambrose et al., 2013). Falls occur when everyday tasks become too difficult (either physically or cognitively) and can lead to various injuries that later affect functioning in old age (Masud and Robert, 2001; Tinetti, 2003; Ambrose et al., 2013). Older adults typically struggle with tasks that must be performed simultaneously, such as using a cell phone and walking down the stairs or simultaneously observing the traffic and stepping off the sidewalk at the same time (Beurskens and Bock, 2012; MacPherson, 2018). This "ability to perform two tasks simultaneously" (MacPherson, 2018) is defined as dual-tasking. Dual-tasking is often challenging for older adults, but the underlying mechanism is not yet clear. Older people engage more cognitive control in mobility tasks (Marusic and Grosprêtre, 2018). This is partly due to age-related sensory impairments and partly due to lower automated motor and cognitive performance (Baltes and Lindenberger, 1997; Li and Lindenberger, 2002; Heuninckx et al., 2005; Wollesen and Voelcker-Rehage, 2014). Human attention is limited (Jiang and Kanwisher, 2003) and both physical and cognitive changes that occur in the brain during aging impair executive functions (Peters, 2006).

Appropriate training, whether motor or cognitive training, can slow down the decline of motor and cognitive functions (Allen et al., 2011; Schoene et al., 2013; Smith et al., 2015; Hortobágyi et al., 2016). Studies are describing different types of exercise for older people to improve mobility-related outcomes; motor training (Allen et al., 2011; Hortobágyi et al., 2016), cognitive training (e.g., Smith et al., 2015), and motor-cognitive dual-task training (e.g., Schoene et al., 2013). Recent systematic reviews have shown that motor (for a review see Plummer et al., 2015) and cognitive training (for a review see Marusic et al., 2018b) can have positive effects on mobility in older adults.

In 2010, two research groups conducted two separate pilot studies that indicated extensive transfer from cognitive training to mobility domain (Li et al., 2010; Verghese et al., 2010). After these two pilot trials, there were many other studies that confirmed this effect, which was also summarized in a meta-analysis (for review see Marusic et al., 2018b). In addition, the various types of non-physical interventions (e.g., cognitive training, motor imagery and action observation) can improve motor-related outcomes (Marusic et al., 2018a; Paravlic et al., 2018, 2019). The potential mechanisms of improved mobility performance after non-physical training sessions have been suggested by intertwined neural circuits and brain substrates involved in both cognitive (executive functions) and mobility processes (Marusic et al., 2018b).

The so-called motor-cognitive training is a type of dual-task training, i.e., it involves two different tasks (the motor task and the cognitive task) that can be performed simultaneously or sequentially (Herold et al., 2018), where one of the tasks specifically challenges motor functions and the other task challenges cognitive functions. In sequential training, the motor task (e.g., walking) and the cognitive task (e.g., solving tasks while sitting at a table and using a desktop computer) are separated (Herold et al., 2018). In simultaneous motor-cognitive training, both motor and cognitive exercises are executed at the same time (Lauenroth et al., 2016; Herold et al., 2018). This type of training can be divided into two types: (i) motor training with cognitive exercises that tend to be unrelated to motor task performance, and (ii) motor training in which successful physical task performance depends on cognitive ability (Herold et al., 2018). If the cognitive exercise appears to be more of a distractor, a simultaneous motor-cognitive training is performed with an additional cognitive task (e.g., cycling while counting backwards from 50 and subtracting 4 s). Conversely, simultaneous motor-cognitive training with a built-in cognitive task (e.g., exergame/exergaming or learning to dance) is conducted when the cognitive exercise fits the content of the intervention as a necessary task to successfully complete the training (Schott, 2015; Manser et al., 2021). Exergaming is defined as technology-based physical activities, such as playing video games, that require participants to be physically active or move in order to play the game. These games require the user to move their entire body to participate in virtual sports, group fitness exercises, or other interactive physical activities (American College of Sports Medicine., 2013).

The different types of motor-cognitive training (sequential, simultaneous with additional or incorporated cognitive task) have not been studied. Therefore, the combination of motor and cognitive intervention has recently gained scientific interest. Several reviews and intervention studies have already reported positive effects of motor-cognitive interventions on single- and dual-task walking and balance in both healthy and cognitively impaired older adults (Law et al., 2014; Fritz et al., 2015; Lauenroth et al., 2016; Zhu et al., 2016; Levin et al., 2017; Raichlen et al., 2020; Chen et al., 2021). However, a systematic investigation on the most effective of all motor-cognitive interventions (sequential, simultaneous with an additional or incorporated cognitive task) effecting gait and balance is not available. Our aim was to identify, summarize, and compare randomized controlled trials (RCTs) examining motor-cognitive intervention approaches vs. single or no training interventions in older adults on selected gait and balance functions.

METHODS

Search Strategy

We performed a systematic literature search in six bibliographic databases, i.e., PubMed, Pedro, Cinahl, SportDiscus, and Scopus. In addition, we performed a literature search on Google Scholar. The search strategy included only terms related to or describing the intervention. Terms were combined with the Cochrane MEDLINE filter for controlled trials of interventions. Our search syntax was: ("motor-cognitive intervention" OR "dual-task" OR "motor-cognitive training" OR "physical-cognitive intervention" OR "motor-cognitive exercise" OR "exergames" OR "serious game" OR "active video game") AND ("gait" OR "walk" OR "walking" OR "mobility" OR "balance" OR "posture") AND ("elderly" OR "old" OR "older" OR "older adult" OR "older adults" OR "aging" OR "elder adults" OR "elders" OR "old-olds"). Search terms were adapted for use with other bibliographic databases in combination with database-specific filters for controlled trials, where these are available. Database searches were supplemented by the review of the authors files. We additionally reviewed the reference list of each included article. We included only studies published in English. When searching for articles, we did not set a time frame for publication. Nevertheless, all articles that met our inclusion criteria were published between 2009 and 2021. The searches were performed again just before the final analysis and additional studies were selected for inclusion. Titles and abstracts that did not meet the inclusion criteria were excluded from the list. The remaining full texts were screened by 3 reviewers (UM, KT, and LŠ). Ultimately, only randomized controlled trials that met the listed inclusion criteria were included.

Selection Criteria

The strategy for the literature search followed the PRISMA (The Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. This is an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses. PRISMA is used as the basis for reporting systematic reviews with objectives. In addition, we included the Problem/Population, Intervention, Comparison, and Outcome (PICO) framework; it can help formulate the search strategy with set of key questions to efficiently find high- quality evidence:

Population: healthy and diseased[1] older adults; the mean age of subjects was over 60 years.
Intervention: motor-cognitive approaches (sequential, simultaneous distractor, simultaneous incorporated).
Comparison: either passive control (neither cognitive nor motor training performed) or motor training groups.
Outcome measures: Gait speed under (m/s) a single- and a dual-task condition, balance performance as measured with Timed Up and Go test (sec) and Berg Balance Scale (points).

We included only randomized controlled trials (RCTs). The inclusion criteria were: (1) the type of outcome measure was gait speed under a single- and/or a dual-task, the Up and Go test and/or the Berg Balance Scale, (2) subjects who performed motor-cognitive interventions were compared with those who performed only motor interventions or subjects who were in the passive control group; (3) the mean age of subjects was greater than 60 years (4) studies in which the effect of interventions was of interest if data were available.

Initially, we included subjects classified as "healthy" older adults with no specific diseases diagnosed and individuals with different diseases such as Parkinson's disease, balance impairment, mild cognitive impairment, osteoporosis, dementia, diabetes mellitus, Alzheimer's disease, and studies, that included either patients after stroke or hospitalized patients or patients with a history of falls, or osteoarthritic patients with balance impairment or older adults who were classified as frail or adults with various motor and cognitive deficits or residents of long-term-care facilities or patients with severe neurocognitive disorders. Because we found a high degree of heterogeneity within the groups diagnosed with a particular deficit, we decided to exclude from further analysis all studies that included diseased individuals. However, we have left a summary of all studies included in the original analysis in **Supplementary Tables 1–4**.

Screening Strategy

Three independent authors (KT, UM, and LŠ) conducted the search for available studies on a selected topic. The screening was performed in four steps. First, the titles were screened by the reviewers to determine whether they were suitable for our meta-analysis. Then, abstracts were assessed to determine whether the study topic met the selected inclusion and exclusion criteria. The

[1]We found a high degree of heterogeneity within the groups diagnosed with a particular deficit, so we decided to exclude all studies that included diseased individuals from further analysis. However, we have left a summary of all studies included in the original analysis in **Supplementary Tables 1–4**.

inclusion criteria were selected as follows (as mentioned above) and are described in **Table 1**: the mean age of the participants was 60 years or more, the type of intervention was a motor-cognitive intervention, the comparison group was either passive or with included motor intervention, the outcomes of the studies were gait speed under a single- or a dual-task condition, TUG and BBS test and the study design was a RCT. The exclusion criteria were: no control group, irrelevant outcomes, unsuitable measurement of gait (e.g., measures were performed on a treadmill), inadequate results and unsuitable measurement of balance (e.g., measures were performed on a force plate). Third, the full text articles were read, the required information was selected and included (if appropriate) in the meta-analysis. Finally, the references of the included studies were reviewed for possible inclusion. If the full text of any paper was unavailable or the data of the study were incomprehensible (certain data on results were missing, e.g., standard deviation, or we were unable to deduce the value of the results from the reported data, e.g., data were reported in graphs), the corresponding author was contacted by email. Disagreements about the inclusion/exclusion of certain RCT were resolved by discussion or by a third person when no consensus could be reached (EdB, AP).

The Physiotherapy Evidence Database (PEDro) scale was used to assess the risk of bias and quality of included studies (Maher et al., 2003). This scale helps the reader to quickly assess whether a clinical trial presents reliable and meaningful results for use in clinical practice. Points are awarded only when a criterion is clearly met. In addition, points are awarded according to the specifics of the article and if the article meets those specifics (eligibility criteria were specified, subjects were randomly assigned to groups, assignment was concealed, the groups were similar at baseline regarding the most important prognostic indicators, there was blinding of all subjects, there was blinding of all therapist who administered the therapy, there was blinding of all assessors who measured at least one key outcome, measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups, all subjects from whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analyzed by "intention to treat", the results of between group statistical comparisons are reported for at least one key outcome). The quality assessment score was interpreted as follows: studies scoring 6–10 points on PEDro quality assessment were of "high quality", studies scoring 4–5 of "fair quality" and studies scoring 0–3 of "poor quality". The evaluation of the studies is available in **Table 2**.

All included studies were divided into three groups (**Tables 3–5**) according to the type of dual-task intervention they performed. According to Herold's definition (Herold et al., 2018), we divided the studies into those that can be performed simultaneously or sequentially. Furthermore, studies that included training with a dual-task performed simultaneously were further divided into studies that performed simultaneous motor-cognitive training with additional cognitive task or those who performed simultaneous motor-cognitive training with incorporated cognitive task. In the category of simultaneous motor-cognitive training with an incorporated cognitive task, there were very few studies that did not use exergaming. We excluded the studies that did not meet the definition of exergaming and formed a group with exergaming studies only. The third group is therefore called exergaming.

TABLE 1 | Inclusion and exclusion criteria.

	Inclusion criteria
Study design	RCT
Language	English
Mean age of participants:	60 years or more
Type of intervention	Motor-cognitive intervention
Comparison group	Passive control group
	Active control group – motor training
Outcomes of the study	Gait speed under a single – task condition
	Gait speed under a dual- task condition
	Timed Up and Go test
	Berg Balance Scale test
	Exclusion criteria
	No control group
	Participants younger than 60 years
	Non-English language
	Unsuitable measurement of balance (e.g., force plate)
	Unsuitable measurement of gait (e.g., treadmill)
	Unsuitable motor-cognitive interventions (e.g., additionally added cognitive tasks during interventions, incorporated cognitive task that was not part of exergame intervention)

Statistical Analysis

The meta-analyses were performed using Comprehensive Meta-analysis software (version 3.0; Biostat Inc., Englewood, NJ, USA). The mean differences and 95% confidence intervals (Cls) were calculated for the included studies. We applied the random-effects model of the meta-analysis in all comparisons to determine the effect of the motor-cognitive intervention on gait and balance. Due to the high heterogeneity of the measured variables, the effect sizes were reported in Hedges-'g. To calculate each effect size we used reported mean value of selected parameter, their standard deviation and sample size of the included study. The following established criteria were used to interpret the magnitude of motor-cognitive intervention for gait and balance improvements: trivial (<0.20), small (0.21–0.60), moderate (0.61–1.20), large (1.21–2.00), very large (2.01–4.00) and extremely large (>4.00) changes (Hopkins et al., 2009; Fraser et al., 2017; Wongcharoen et al., 2017; Laatar et al., 2018). Heterogeneity across studies was assessed using the I^2 statistics, which is a measure of inconsistency used to quantify between-study variability. A value of 25% is recommended to represent low statistical heterogeneity, 50% moderate and 75% high statistical heterogeneity (Higgins, 2003). In addition, the sensitivity analysis excluded studies with poor methodological quality, i.e., the study's PEDro score was 3 or less. The publication

TABLE 2 | Quality assessment of included studies with healthy older adults according to PEDro scale.

Study	Quality criteria											Quality score
	1	2	3	4	5	6	7	8	9	10	11	
Bieryla and Dold (2013)	X	X	-	X	-	-	-	-	-	-	-	3
Bieryla (2016)	X	X	-	X	-	-	-	-	X	X	X	6
Bischoff et al. (2020)	X	X	-	X	-	-	X	-	-	X	X	5
de Bruin et al. (2013)	X	X	-	X	-	-	-	-	-	X	X	5
Chao et al. (2015)	X	X	-	X	-	-	-	X	-	X	X	6
Desjardins-Crepeau et al. (2016)	X	X	-	X	-	-	X	-	-	X	X	6
Eggenberger et al. (2015)	X	X	-	X	-	-	-	-	X	X	X	5
Eggenberger et al. (2016)	X	X	-	X	-	-	-	-		X	-	3
Falbo et al. (2016)	X	X	-	X	-	-	-	-	-	X	X	5
Franco et al. (2012)	X	X	-	X	-	-	-	X	-	X	X	6
Fraser et al. (2017)	X	X	-	X	-	-	-	-	-	X	X	5
Gallardo-Meza et al. (2022)	X	X	-	X	-	-	-	X	X	-	X	6
Gregory et al. (2016)	X	X	X	X	-	-	X	-	X	X	X	8
Gschwind et al. (2015)	-	X	-	X	-	-	-	X	X	X	X	6
Gschwind et al. (2015)	X	X	-	X	-	-	-	X	X	X	X	7
Hiyamizu et al. (2012)	X	X	X	X	-	-	X	-	X	X	X	8
Jardim et al. (2021)	X	-	-	X	-	-	-	X	X	X	X	6
Jehu et al. (2017)	X	X	-	X	-	-	-	X	-	X	X	6
Jorgensen et al. (2013)	X	X	-	X	-	-	X	X	X	X	X	8
Kao et al. (2018)	X	X	X	X	X	X	-	X	-	X	-	8
Karahan et al. (2015)	X	X	-	X	-	-	-	X	X	X	X	7
Kwok and Pua (2016)	X	X	X	X	-	-	X	-	-	X	X	7
Lai et al. (2013)	-	X	-	X	-	-	X	-	-	-	X	4
Lee et al. (2015)	X	X	-	X	-	-	X	X	X	X	X	8
Lee et al. (2018)	X	X	-	X	-	-	X	X	-	X	X	7
Maillot et al. (2012)	X	X	-	X	-	-	-	X	X	-	X	6
Medeiros et al. (2018)	X	X	-	X	-	-	-	X	X	X	X	7
Morat et al. (2019)	X	X	-	X	-	-	-	X	-	X	X	6
Nagano et al. (2016)	X	X	X	-	-	-	X	X	X	X	X	8
Nematollahi et al. (2016)	X	X	X	X	X	X	-	-	X	X	X	8
Ng et al. (2015)	X	X	X	X	-	-	X	X	X	X	X	9
Nishiguchi et al. (2015)	X	X	-	X	-	-	X	X	-	X	X	7
Norouzi et al. (2019)	X	X	X	X	-	-	-	X	X	X	X	8
Padala et al. (2012)	X	X	-	X	-	-	-	-	X	X	X	6
Park et al. (2015)	-	X	-	X	-	-	-	-	-	X	X	4
Phirom et al. (2020)	X	X	X	-	-	-	-	X	-	X	X	6
Pichierri et al. (2012)	X	X	-	X	-	-	-	-	-	X	X	5
Pluchino et al. (2012)	X	X	X	X	-	-	-	-	-	X	X	6
Plummer-D'Amato et al. (2012)	X	X	X	X	-	-	X	X	-	X	X	8
Pothier et al. (2018))	-	X	-	X	-	-	-	-	-	X	X	4
Raichlen et al. (2020)	X	X	-	X	-	-	X	-	X	X	X	7
Rendon et al. (2012)	X	X	-	X	-	-	X	-	X	X	X	7
Rezola-Pardo et al. (2019)	X	X	X	X	-	-	X	-	X	X	X	8
Sadeghi et al. (2021)	X	X	X	-	-	-	-	-	X	X	X	6
Salazar-González et al. (2015)	X	X	X	X	-	-	-	-	X	X	X	7
Sápi et al. (2019)	X	-	-	-	-	-	-	-	-	X	X	3
Sato et al. (2015)	-	X	-	X	-	-	-	X	-	X	X	6
Schättin et al. (2016)	X	X	-	X	-	-	-	X	-	X	X	6
Schoene et al. (2013)	X	X	X	X	-	-	X	X	-	X	X	8

(Continued)

TABLE 2 | Continued

Study	Quality criteria											Quality score
	1	2	3	4	5	6	7	8	9	10	11	
Schwenk et al. (2014)	X	X	X	X	-	-	-	X	-	X	X	7
Sipilä et al. (2021)	X	X	-	X	-	-	X	X	X	X	X	8
Theill et al. (2013)	X	-	-	X	-	-	-	-	-	X	X	4
van het Reve and de Bruin (2014)	X	X	X	X	X	-	-	X	X	X	X	9
Yamada et al. (2011a)	X	X	X	X	-	-	X	X	-	X	X	8
Yamada et al. (2011b)	X	X	X	X	-	-	X	X	-	X	X	8
Yesilyaprak et al. (2016)	X	X	-	X	-	-	X	X	-	X	X	7
Yoo et al. (2013)	-	X	-	X	-	-	-	X	-	X	X	5
Wongcharoen et al. (2017)	X	X	X	X	-	-	X	X	-	X	-	7

**1-eligibility criteria were specified, 2-subjects were randomly allocated to groups, 3-allocation was concealed, 4-the groups were similar at baseline regarding the most important prognostic indicators, 5-there was blinding of all subjects, 6-there was blinding of all therapists who administered the therapy, 7-there was blinding of all assessors who measured at least one key outcome, 8-measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups, 9-all subjects from whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analyzed by ≫intention to treat≪, 10-the results of between-group statistical comparisons are reported for at least one key outcome, the study provides both point measures and measures of variability for at least one key outcome.*

bias was assessed by examining the asymmetry of the funnel plots using Egger's test (Egger et al., 1997; Sterne et al., 2011). Significant publication bias was considered if the p - value was < 0.10.

RESULTS

The Egger's test was performed to provide statistical evidence of funnel plot asymmetry (see **Supplementary Figures 2A–D**). The results indicated publication bias for TUG only ($P = 0.003$).

Study Selection

The initial search yielded 6,314 results. After duplicates were removed, 2,546 articles remained to be considered. After screening titles and abstracts, 890 records were excluded. Full-text reading of 351 articles revealed that 262 articles did not meet our inclusion criteria. We excluded 262 articles with the following reasons: no matched control group in the study ($n = 44$), unsuitable protocol (e.g., only intervention group, without control group) ($n = 20$), irrelevant outcomes ($n = 32$), unsuitable motor-cognitive interventions (e.g., additionally added cognitive tasks during interventions, incorporated cognitive task that was not part of exergame intervention) ($n = 81$), unsuitable measurement of gait (e.g., measures were performed on a treadmill) ($n = 11$), inadequate outcomes ($n = 20$), and unsuitable measurement of balance (e.g., measures were performed on a force plate) ($n = 6$) and not randomized controlled trials ($n = 48$). After excluding studies that included diseased older adults, there were 58 studies that we included in the quantitative synthesis. Details of the study selection process are presented in **Supplementary Figure 1**.

Characteristics of Included Studies

Based on the quality assessment, 44 out of 58 studies were high quality, 11 of fair quality and only 3 of low quality (**Table 2**). The intervention characteristics, including the type of intervention, a description of the motor and cognitive components and the frequency and dose of training described in the included studies are summarized in **Tables 3–5**. To facilitate the review of included studies, we have subdivided all studies according to the type of training performed by the experimental group (sequential motor-cognitive training, simultaneous motor cognitive training with additional cognitive task and exergaming).

We included 7 studies with sequential motor-cognitive training (presented in **Table 3**). These studies included samples ranging from 14 to 147 participants (range of age 69.7–81.9 years). The most common training approach ($N = 6$) was a combination of aerobic/resistance/strength/balance training and performing cognitive tasks on the PC.

There were 19 studies with simultaneous motor-cognitive training with an additional cognitive task (presented in **Table 4**). Studies included samples ranging from 17 to 286 participants, with the age of participants in both groups (experimental and control group) varying from 64.7 to 85.3 years. The most common training approach used was a combination of balance training while simultaneously performing different cognitive tasks (the number of studies with that type of training is 9).

We included 33 studies that performed exergaming (**Table 5**). Studies included samples ranging from 9 to 153 participants. The age range of participants in both groups (experimental and control) was between 65.2 and 86.9 years. The training approach in the studies included different types of interventions using PC and consoles with game controls, e.g., Nintendo Wii and Xbox Kinect, as one form of exergaming training offered to the participants.

TABLE 3 | Sequential motor-cognitive training.

Study	Sample description	Experimental design and duration of trial period	Control design and duration of trial period	Outcomes and results
Desjardins-Crepeau et al. (2016)	$N = 76$ (CON ST = 18, CON AR = 16, EXP ARdt = 22, EXP STdt = 20) Mean $age_{CONST} = 72.5 \pm 7.0$ Mean $age_{CONAR} = 70.9 \pm 7.4$ Mean $age_{EXPARdt} = 72.7 \pm 7.4$ Mean $age_{EXPSTdt} = 73.2 \pm 6.3$	ARdt = In addition to the aerobic and resistance training participants performed cognitive training on a PC (visual discrimination tasks performed separately and concurrently) STdt = In addition to stretching and toning training participants performed cognitive training on a PC (visual discrimination tasks performed separately and concurrently) PA training: 12 weeks: 2-times per week (60 min/trial) Cognitive training: 12 weeks: 1-time per week (60 min/trial)	AR = Aerobic exercises + passive computer lessons (excel, word) ST = Stretching exercises + passive computer lessons (excel, word) 12 weeks: 3-times per week (2x-physical exercise + 1x-passive computer lessons; 60 min/trial)	TUG (no improvement) Gait speed (6MWT) ↑ for CON and EXP group
Pothier et al. (2018)	$N = 90$ (CON ST = 18, CON AR = 21, EXP ARdt = 28, EXP STdt = 23) Mean $age_{CONST} = 72.5 \pm 6.9$ Mean $age_{CONAR} = 69.7 \pm 6.5$ Mean $age_{EXPARdt} = 72.2 \pm 7.0$ Mean $age_{EXPSTdt} = 74.2 \pm 6.9$	ARdt = In addition to the aerobic and resistance training participants performed cognitive training on a PC (number and shape discrimination tasks) STdt = In addition to stretching and toning training participants performed cognitive training on a PC (number and shape discrimination tasks) PA training: 12 weeks: 2-times per week (60 min/trial) Cognitive training: 12 weeks: 1-time per week (60 min/trial)	AR = Aerobic exercises + passive computer lessons (excel, word) ST = Stretching exercises + passive computer lessons (excel, word) 12 weeks: 3-times per week (2x-physical exercise + 1x-computer lessons; 60min/trial)	Gait speed - ↑ for both EXP group and CON AR
van het Reve and de Bruin (2014)	$N = 145$ (CON = 76, EXP = 69); Mean $age_{CON} = 81.9 \pm 6.3$ Mean $age_{EXP} = 81.1 \pm 8.3$	In addition to the strength and balance training participants performed CogniPlus program. PA training: 12 weeks: 2-times per week (40 min/trial) Cognitive training: 12 weeks: 3-times per week (10 min/trial)	Strength and balance training 12 weeks, 2-times per week (40 min/trial)	Gait speed (no improvement) ETGUG – ↑ for CON and EXP group
de Bruin et al. (2013)	$N = 14$ (CON = 7, EXP = 7); Mean $age_{CON} = 75.0 \pm 8.3$ Mean $age_{EXP} = 79.8 \pm 6.9$	In addition to the strength and balance training participants performed CogniPlus program PA training: 12 weeks, 2-times per week (45–60 min/trial) Cognitive training: 10 weeks: 3 to 5-times per week (10 min/trial)	Strength and balance training 12 weeks, 2-times per week (45–60 min/trial)	ETGUG - ↑ for CON and EXP
Ng et al. (2015)	$N = 147$ (CON passive = 50, CON motor = 48, EXP = 49) Mean $age_{CONpassive} = 70.1 \pm 5.0$ Mean $age_{CONmotor} = 70.3 \pm 5.2$ Mean $age_{EXP} = 70.4 \pm 4.7$	In addition to the strength and balance training participants performed cognitive training (stimulate short term memory, enhance attention and information-processing skills and reasoning and problem solving abilities) PA training: 12 weeks: 2-times per week (90 min/trial) + 12 weeks home based exercises	CON passive = Passive group (only pre- and post-intervention assessment) CON motor = The exercise program was designed to improve strength and balance	Gait speed (6MWT) ↑ for CON motor
Fraser et al. (2017)	$N = 72$ (CON ST = 16, CON AR = 17, EXP ARdt = 21, EXP STdt = 18) Mean $age_{CONST} = 71.1 \pm 5.4$ Mean $age_{CONAR} = 70.5 \pm 7.3$ Mean $age_{EXPARdt} = 71.9 \pm 6.8$ Mean $age_{EXPSTdt} = 72.2 \pm 5.9$	ARdt = In addition to the aerobic and resistance training participants performed cognitive training on a PC (two visual discrimination tasks) STdt = In addition to stretching and toning training participants performed cognitive training on a PC (two visual discrimination tasks) PA training: 12 weeks: 2-time per week (60 min/trial) Cognitive training: 12 weeks: 1-time per week (60 min/trial)	AR = Aerobic exercises + passive computer lessons (excel, word) ST = Stretching exercises + passive computer lessons (excel, word) 12 weeks: 3-times per week (2x-physical exercise + 1x-computer lessons; 60 min/trial)	Gait speed - DT – ↑ for both CON and both EXP group

(Continued)

TABLE 3 | Continued

Study	Sample description	Experimental design and duration of trial period	Control design and duration of trial period	Outcomes and results
Sipilä et al. (2021)	$N = 314$ (CON=159, EXP = 155) Mean $age_{CON} = 74.5 \pm 3.7$ Mean $age_{EXP} = 74.4 \pm 3.9$	In addition to strength, balance, and aerobic training participants performed cognitive training on a PC (learning general computer skills) PA training: 1 year: 2-time per week (45 min/trial) + 2–3-times per week home based training (20–30 min/trial) Cognitive training: 1 year: 3–4-time per week (15–20 min/trial)	Strength, balance, and aerobic training 1 year: 2-time per week (45 min/trial) + 2–3-times per week home based training (20–30 min/trial)	Gait speed – ↑ for CON and EXP group

Meta-Analysis Outcomes (Domain-Specific Efficacy)

Gait Speed Under a Single-Task Condition

Forty-one studies (41 ESs) were included to assess the effect of motor-cognitive intervention on gait speed under a single-task condition. The results showed that the motor-cognitive intervention has a small positive effect on gait speed under a single-task condition (ES = 0.34, 95% Cl 0.12 to 0.57, $P = 0.003$). The effect of the intervention was moderated by the control group (Q = 6.203, $P = 0.013$); i.e., passive (ES = 0.941, 95% Cl 0.36 to 1.52, $P = 0.001$) vs. active (ES = 0.153, 95% Cl −0.07 to 0.38, $P = 0.180$). The type of intervention did not bring significant differences where additional, incorporated, and sequential intervention had the same effect on gait speed under a single task (Q = 0.668; $P = 0.716$). Even after excluding the study (Eggenberger et al., 2016) that had a low PEDro score (PEDro score = 3), the results showed a small positive effect of the motor-cognitive intervention on a gait speed under a single-task condition (ES = 0.35, 95% Cl 0.12 to 0.58, $P = 0.003$) and the effect of the intervention was moderated by the control group ($Q = 6.067$, $P = 0.014$); i.e., passive (ES = 0.941, 95% Cl 0.36 to 1.52, $P = 0.001$) vs. active (ES = 0.159, 95% Cl −0.07 to 0.39, $P = 0.177$). Moreover, once again the type of intervention did not bring significant difference on a gait speed under a single task ($Q = 0.799$; $P = 0.671$).

Gait Speed Under a Dual-Task Condition

Twenty studies (20 ESs) were included to assess the effect of motor-cognitive intervention on gait speed under a dual-task condition. The results showed that the motor-cognitive intervention has no significant effect on gait speed under a dual-task condition (ES = 0.22, 95% Cl −0.01 to 0.44, $P = 0.063$). There was no significant difference between different control groups ($Q = 0.003$; $P = 0.957$) nor the type of intervention (Q = 0.213; $P = 0.899$).

Timed Up and Go Test

Forty-one studies (41 ESs) were included to assess the effect of motor-cognitive intervention on TUG test. The results showed that the motor-cognitive intervention has a small positive effect on TUG (ES = 0.42, 95% Cl 0.21 to 0.63, $P < 0.001$). The effect of the intervention was moderated by the control group (Q = 4.92; $P = 0.027$); i.e., passive (ES = 0.73, 95% Cl 0.30 to 1.15, $P = 0.001$) vs. active (ES = 0.20, 95% Cl 0.03 to 0.38, $P = 0.020$), but not by the type of training ($Q = 5.51$; $P = 0.064$). After conducting sensitivity analysis by excluding two studies with low PEDro score (Bieryla and Dold, 2013; Sápi et al., 2019), the results still showed a small positive effect of the motor-cognitive intervention on TUG results (ES = 0.35, 95% Cl 0.15 to 0.55, $P = 0.001$) and the effect of the intervention was still moderated by the control group ($Q = 4.280$, $P = 0.039$); i.e., passive (ES = 0.619, 95% Cl 0.22 to 1.02, $P = 0.003$) vs. active (ES = 0.160, 95% Cl 0.001 to 0.320, $P = 0.048$). There was no significant difference between different types of intervention after excluding low quality studies.

Berg Balance Scale

Eleven studies (11 ESs) were included to assess the effect of motor-cognitive intervention on BBS score. The results showed that the motor-cognitive intervention has a small positive effect on BBS (ES = 0.59, 95% Cl 0.39 to 0.79, $P < 0.001$). There was no difference between active or passive control group ($Q = 0.397$; $P = 0.529$) and no difference between the type of intervention ($Q = 0.299$; $P = 0.585$).

DISCUSSION

The aim of the present systematic review and meta-analysis was to investigate whether motor-cognitive interventions can have a positive impact on selected gait and balance parameters in older adults. We contrasted the effects of passive and active control groups as well as three different types of motor-cognitive training. We focused on motor-cognitive interventions such as dual-task training and included studies with healthy older adults. Because of high heterogeneity in the studies performed in diseased older adults, we excluded them and performed the analysis only on healthy older people. To increase sensitivity, we additionally excluded three studies from the analysis that were of poor quality according to the PEDro assessment.

Overall, we found evidence that motor-cognitive interventions can improve gait speed under single-task condition, and measures of functional balance, but they have no significant effects on dual-task walking outcomes. However, motor-cognitive intervention does not necessarily have a better effect on gait speed under single-task improvement than active control group, which in this case is conventional motor training. On the other hand, there was a small but significant effect in

TABLE 4 | Simultaneous motor-cognitive training with additional cognitive task.

Study	Sample description	Experimental design and duration of trial period	Control design and duration of trial period	Outcomes and results
Norouzi et al. (2019)	$N = 60$ (CON passive = 20, CON motor = 20, EXP = 20) Mean $age_{CONpassive} = 68.1 \pm 3.7$ Mean $age_{CONmotor} = 68.3 \pm 4.1$ Mean $age_{EXP} = 68.5 \pm 3.6$	Resistance training wearing an isokinetic exercise device while simultaneously performing cognitive tasks (backward number counting, mental arithmetic, calculate the assignment to front, spelling particular names backwards, counting numbers backwards in intervals of 3 and 7, remembering words given in 300 ms intervals, remembering visual images, remembering shapes, remembering colors, differentiating between shapes, remembering the order of a word list). Four weeks: 3-times per week (60–80 min/trial)	CON passive = Passive group (only pre- and post-intervention assessment) CON motor = Resistance training with an isokinetic exercise device plus simultaneous motor training (skill training – throwing a bag, holding a bag, balancing the cup on the palm of the hand, holding a medicine ball in both hands)	BBS – ↑ for CON motor and EXP group
Eggenberger et al. (2015)	$N = 47$ (CON = 25, EXP = 22) Mean $age_{CON} = 80.8 \pm 4.7$ Mean $age_{EXP} = 78.5 \pm 5.1$	Treadmill walking while simultaneously performing cognitive tasks (verbal memory tasks) strength and balance exercises. 24 weeks: 2-times per week (60 min/trial)	Treadmill walking + strength and balance training 24 weeks: 2-times per week (60 min/trial)	Gait speed – ↑ for CON and EXP group Gait speed - DT – ↑ for CON and EXP group
Rezola-Pardo et al. (2019)	$N = 85$ (CON = 43, EXP = 42) Mean $age_{CON} = 85.3 \pm 7.1$ Mean $age_{EXP} = 84.9 \pm 6.7$	Strength and balance training while simultaneously performing cognitive tasks (different tasks to stimulate attention, executive functions and semantic memory). 12 weeks: 2-time per week (60 min/trial)	Strength and balance exercises 12 weeks: 2-time per week (60 min/trial)	Gait speed – ↑ for CON and EXP group, Gait speed - DT – ↑ for CON and EXP group TUG – ↑ for CON
Raichlen et al. (2020)	$N = 53$ (CON motor = 19, CONpassive = 14, EXP = 20) Mean $age_{CONmotor} = 68.1 \pm 3.9$ Mean $age_{CONpassive} = 69.3 \pm 4.3$ Mean $age_{EXP} = 68.0 \pm 4.7$	Aerobic training while simultaneously performing cognitive tasks (memory, executive functions and processing speed exercises). 12 weeks: 3-time per week (20–35 min/trial)	CON motor = Aerobic exercise CON passive = Passive group (only pre- and post-intervention assessment) 12 weeks: 3-time per week (20–35 min/trial)	Gait speed -DT (no improvements)
Plummer-D'Amato et al. (2012)	$N = 17$ (CON = 7, EXP = 10) Mean $age_{CON} = 76.7 \pm 6.0$ Mean $age_{EXP} = 76.6 \pm 5.6$	Gait and balance training while simultaneously performing cognitive tasks (random number generation, word association, backward recitation, working memory). 4 weeks: 1-times per week (45 min/trial)	Gait, balance, and agility training 4 weeks: 1-time per week (45 min/trial)	Gait speed – ↑ for CON and EXP group, TUG – ↑ for CON and EXP group
Hiyamizu et al. (2012)	$N = 36$ (CON = 19, EXP = 17) Mean $age_{CON} = 71.2 \pm 4.4$ Mean $age_{EXP} = 72.9 \pm 5.1$	Strength and balance training while simultaneously performing cognitive tasks. 12 weeks: 2-times per week (60 min/trial)	Strength and balance training 12 weeks: 2-times per week (60 min/trial)	TUG (no improvement)
Wongcharoen et al. (2017)	$N = 30$ (CON motor = 15, EXP = 15) Mean $age_{CONmotor} = 73.5 \pm 5.9$ Mean $age_{EXP} = 71.9 \pm 4.6$	Balance training while simultaneously performing cognitive tasks (visuospatial skills, executive functions, attention, and working memory exercises). 4 weeks: 3-times per week (60 min/trial)	CON motor = Balance training 4 weeks: 3-times per week (60 min/trial)	Gait speed - ↑ for CON motor and EXP group. Gait speed - DT – - ↑ for CON motor and EXP group.
Nematollahi et al. (2016)	$N = 29$ (CON = 14, EXP = 15) Mean $age_{CON} = 67.7 \pm 5.0$ Mean $age_{EXP} = 64.7 \pm 5.0$	Balance training while simultaneously performing cognitive tasks (adding numbers, counting backwards by 3s during narrow-base walking, naming the opposite direction of their actions). 4 weeks: 3-times per week (60 min/trial)	Balance training 4 weeks: 3-times per week (60 min/trial)	Gait speed (no improvement)
Gregory et al. (2016)	$N = 44$ (CON = 21, EXP = 23) Mean $age_{CON} = 74.5 \pm 7.0$ Mean $age_{EXP} = 72.6 \pm 7.4$	Aerobic, strength, balance, and flexibility training while simultaneously performing cognitive tasks (beginner-level square stepping exercise). 26 weeks: 2–3-times per week (60–75 min/trial)	Aerobic, strength, balance, and flexibility training 26 weeks: 2–3-times per week (60–75 min/trial)	Gait speed – DT - ↑ for EXP group
Nishiguchi et al. (2015)	$N = 48$ (CON = 24, EXP = 24) Mean $age_{CON} = 73.5 \pm 5.6$ Mean $age_{EXP} = 73.0 \pm 4.8$	Walking training while simultaneously performing different cognitive tasks (different verbal fluency tasks) 12 weeks: 1-time per week (90 min/trial)	Passive group (only pre- and post-intervention assessment)	Gait speed - ↑ EXP group TUG (no improvement)

(Continued)

TABLE 4 | Continued

Study	Sample description	Experimental design and duration of trial period	Control design and duration of trial period	Outcomes and results
Yamada et al. (2011a)	*N* = 53 (CON = 27, EXP = 26) Mean age$_{CON}$ = 81.2 ± 7.6 Mean age$_{EXP}$ = 80.3 ± 5.4	Stepping training while simultaneously performing cognitive tasks (different verbal fluency tasks) 24 weeks: 1-time per week (50 min/trial)	Stepping training 24 weeks: 1-time per week (50 min/trial)	Gait speed - DT – ↑ EXP group Gait speed and TUG (no improvement)
Yamada et al. (2011b)	*N* = 93 (CON = 45, EXP = 48) Mean age$_{CON}$ = 82.9 ± 5.5 Mean age$_{EXP}$ = 83.0 ± 6.7	Stretching, strength and agility training (seated) + seated stepping exercise while simultaneously performing cognitive tasks (verbal fluency tasks such as listing wirds within a category at a self selected speed) 24 weeks: 2-time per week (20 min/trial)	Passive group (only pre- and post-intervention assessment)	Gait speed - DT – ↑ EXP group Gait speed and TUG (no improvement)
Theill et al. (2013)	*N* = 41 (CON passive = 21, EXP = 18) Mean age$_{CONpassive}$ = 70.9 ± 4.8 Mean age$_{EXP}$ = 72.4 ± 4.2	Treadmill walking while simultaneously performing cognitive tasks (computer based tasks). 10 weeks: 2-times per week (40 min/trial)	CON passive = Passive group (participants were tested before and after intervention) 10 weeks: 2-times per week (15 min/trial)	Gait speed – ↑ for CON and EXP group, Gait speed - DT – ↑ for CON and EXP group,
Salazar-González et al. (2015)	*N* = 286 (CON = 143, EXP = 143) Mean age$_{CON}$ = 74.0 ± 6.3 Mean age$_{EXP}$ = 71.0 ± 5.7	Treadmill walking while simultaneously performing cognitive tasks. 12 weeks: 3-times per week (60 min/trial)	Passive group (participants were tested before and after intervention)	Gait speed – ↑ for EXP group
Jehu et al. (2017)	*N* = 26 (CONpassive= 12, CONmotor = 15, EXP = 14) Mean age$_{CONpassive}$ = 66.3 ± 4.4 Mean age$_{CON\ motor}$ = 70.2 ± 3.1 Mean age$_{EXP}$ = 68.7 ± 5.5	Balance training while simultaneously performing cognitive tasks. 12 weeks: 3-times per week (60 min/trial)	CONpassive = Passive group (only pre- and post-intervention assessment) CONmotor = Balance and mobility training 12 weeks: 3-times per week (60 min/trial)	TUG – ↑ for CON motor and EXP group
Medeiros et al. (2018)	*N* = 71 (CON = 36, EXP = 35) Mean age$_{CON}$ = 68.1 ± 6.4 Mean age$_{EXP}$ = 67.8 ± 8.6	Aerobic, flexibility, strength, and balance training while simultaneously performing cognitive tasks. 12 weeks, 3-times per week (50 min/trial)	Aerobic, flexibility, strength, and balance training 12 weeks: 3-times per week (50 min/trial)	TUG (no improvement)
Bischoff et al. (2020)	*N* = 24 (CON = 2, EXP = 5) Mean age$_{CON}$ = 83.8 ± 5.7 Mean age$_{EXP}$ = 83.6 ± 7.3	Balance, coordination, aerobic and strength training while simultaneously performing cognitive tasks. 16 weeks: 2-times per week (45 - 60 min/trial)	Balance, coordination, aerobic and strength training 16 weeks: 2-times per week (45–60 min/trial)	Gait speed
Jardim et al. (2021)	*N* = 72 (CON = 31, EXP = 41) Mean age$_{CON}$ = 83.8 ± 5.7 Mean age$_{EXP}$ = 83.6 ± 7.3	Aerobic, resistance, and stretching training while simultaneously performing cognitive tasks. 12 weeks: 2-times per week (75 min/trial)	Passive group (only pre- and post-intervention assessment)	Gait speed – ↑ for EXP group TUG – ↑ for EXP group
Falbo et al. (2016)	*N* = 36 (CON = 16, EXP = 20) Mean age$_{CON}$ = 73.7 ± 4.5 Mean age$_{EXP}$ = 71.5 ± 6.7	Aerobic, strength, agility, balance and stretching training while simultaneously performing cognitive tasks relying on executive functions. 12 weeks: 2-time per week (60 min/trial)	Aerobic, strength, agility, balance and stretching training while simultaneously performing physical dual task exercise.	Gait speed -DT

favor of motor-cognitive interventions compared with other conventional motor interventions for TUG. Finally, we found that most studies conducted motor-cognitive training with additional cognitive tasks ($n = 53$), fewer studies conducted exergaming training (48). The least research has been conducted with sequential motor-cognitive training ($n = 8$). However, the studies differed in terms of intervention protocol, frequency, dosage of training, and sample size. Therefore, considerable heterogeneity was found among the included studies in terms of the methodology used. In the next sections we discuss the results per outcomes of interest in some more detail.

Gait Speed Under a Single-Task Condition

Our meta-analysis showed that motor-cognitive intervention can improve gait speed under single-task conditions. There was a small but significant effect that suggests that motor-cognitive interventions for this specific gait parameter may be beneficial for healthy older adults. However, further analysis showed that such interventions are no more effective than other conventional interventions in improving gait speed under a single-task conditions and that the type of motor-cognitive intervention is not a moderating factor for a positive effect.

Although walking was considered a fairly simple task until recently, it requires a large amount of higher-level cognitive input (Mirelman et al., 2018). For this reason, we hypothesized that motor-cognitive interventions would be more beneficial compared to motor training alone. The fact that motor-cognitive training does not contribute more to gait improvement in the active comparison groups than conventional forms of motor

TABLE 5 | Exergaming.

Study	Sample description	Experimental design and duration of trial period	Control design and duration of trial period	Outcomes and results
Eggenberger et al. (2015)	$N = 49$ (CON = 25, EXP = 24) Mean $age_{CON=}$ 80.8 ± 4.7 Mean age_{EXP} = 77.3 ± 6.3	Video game dancing + strength and balance exercises 24 weeks: 2-times per week (60 min/trial)	Treadmill walking + strength and balance training 24 weeks: 2-times per week (60 min/trial)	Gait speed – ↑ for CON and EXP group Gait speed - DT – ↑ for CON and EXP group
Morat et al. (2019)	$N = 30$ (CON = 15, EXP = 15) Mean age_{CON} = 71.1 ± 5.2 Mean age_{EXP} = 69.7 ± 6.2	Volitional stepping exergame on the Dividat Senso device 8 weeks: 3-times per week (40 min/trial)	Passive group (only pre- and post-intervention assessment)	TUG – ↑ for EXP group
Phirom et al. (2020)	$N = 39$ (CON = 19, EXP = 20) Mean age_{CON} = 71.1 ± 5.2 Mean age_{EXP} = 69.7 ± 6.2	Xbox 360 Kinect – stepping on different targets and in different directions, and balance training. 12 weeks: 3-times per week (60 min/trial)	Passive group (only pre- and post-intervention assessment)	TUG – ↑ for EXP group
Kao et al. (2018)	$N = 62$ (CON = 31, EXP = 31) Mean age_{CON} = 72.3 ± / Mean age_{EXP} = 73.5 ± /	Hot Plus interactive health service system – psychomotor skills training 8 weeks: 3-times per week (30 min/trial)	Active control group by use of a tablet computer for the passive information activity.	Gait speed (no improvement)
Karahan et al. (2015)	$N = 90$ (CON = 42, EXP = 48) Mean age_{CON} = 71.5 ± 4.7 Mean age_{EXP} = 71.3 ± 6.1	Xbox 360 Kinect 6 weeks: 5-times per week (30 min/trial)	Home-based balance training 6 weeks: 5-times per week (30 min/trial)	BBS – ↑ for CON and EXP group TUG – ↑ for EXP group
Pichierri et al. (2012)	$N = 21$ (CON = 10, EXP = 11) Mean age_{CON} = 85.6 ± 4.2 Mean age_{EXP} = 86.9 ± 5.1	Resistance and balance training + video game dancing 12 weeks: PA: 2-times per week (40 min/trial) + video game dancing: 2-times per week (10–15 min/trial)	Resistance and balance training 12 weeks: PA: 2-times per week (40 min/trial)	Gait speed (no improvement) Gait speed - DT – ↑ for CON and EXP group,
Schwenk et al. (2014)	$N = 33$ (CON = 16, EXP = 17) Mean $age_{CON=}$ 84.9 ± 6.6 Mean age_{EXP} = 84.3 ± 7.3	Balance training including weight shifting and virtual obstacle crossing tasks with visual/auditory real-time joint movement feedback using wearable sensors. 4 weeks: 2-times per week (45 min/trial)	Passive group (only pre- and post-intervention assessment)	Gait speed – ↑ EXP group TUG – ↑ for EXP group
Schoene et al. (2013)	$N = 32$ (CON = 17, EXP = 15) Mean $age_{CON=}$ 78.4 ± 4.5 Mean age_{EXP} = 77.5 ± 4.5	Step training using a videogame technology (DDR) 8 weeks: 2–3-times per week (15–20 min/trial)	Passive group (only pre- and post-intervention assessment)	TUG (no improvement)
Bieryla and Dold (2013)	$N = 9$ (CON = 5, EXP = 4) Mean $age_{CON=}$ 80.5 ± 7.8 Mean age_{EXP} = 82.5 ± 1.6	Wii Balance Board with Wii Fit training 3 weeks: 3-times per week (30 min/trial)	Passive group (only pre- and post-intervention assessment)	TUG (no improvement)
Bieryla (2016)	$N = 12$ (CON = 7, EXP = 5) Mean $age_{CON=}$ 82.6 ± 6.9 Mean age_{EXP} = 82.0 ± 2.4	Xbox Kinect training to improve balance. 3 weeks: 3-times per week (30 min/trial)	Passive group (only pre- and post-intervention assessment)	BBS – ↑ for EXP group TUG (no improvement)
Chao et al. (2015)	$N = 32$ (CON = 16, EXP = 16) Mean $age_{CON=}$ 83.7 ± 8.0 Mean age_{EXP} = 86.6 ± 4.2	Wii Fit training 4 weeks: 2-times per week (30 min/trial)	Health educational session 4 weeks: 1-times per week (30 min/trial)	BBS – ↑ for EXP group TUG – ↑ for EXP group Gait speed (6MWT) (no improvement)
Sápi et al. (2019)	$N = 53$ (CONmotor= 23, CONpassive = 22, EXP = 30) Mean $age_{CON\ motor}$ = 69.7 ± 4.7 Mean $age_{CON\ passiver}$ = 67.2 ± 5.6 Mean age_{EXP} = 69.1 ± 4.2	Kinect balance training 6 weeks: 3-times per week (30 min/trial)	CONmotor = Conventional balance training CONpassive= Passive group (only pre- and post-intervention assessment) 6 weeks: 3-times per week (30 min/trial)	TUG – ↑ for CON motor and EXP group
Sato et al. (2015)	$N = 54$ (CON = 26, EXP = 28) Mean $age_{CON=}$ 68.5 ± 5.5 Mean age_{EXP} = 70.1 ± 5.3	Kinect training 12 weeks: 1-2-times per week (30 min/trial)	Passive group (only pre- and post-intervention assessment)	Gait speed BBS – ↑ for EXP group
Schättin et al. (2016)	$N = 27$ (CON = 14, EXP = 13) Mean $age_{CON=}$ 72.2 ± / Mean age_{EXP} = 73.0 ± /	Exergame training 8 weeks: 3-times per week (30 min/trial)	Conventional balance training 8 weeks: 3-times per week (30 min/trial)	Gait speed – ↑ CON group Gait speed - DT – ↑ for EXP group

(Continued)

TABLE 5 | Continued

Study	Sample description	Experimental design and duration of trial period	Control design and duration of trial period	Outcomes and results
Sadeghi et al. (2021)	*N* = 44 (CON motor = 14, CON passive = 15, EXP = 15) Mean $age_{CONmotor}$ = 70.4 ± 4.3 Mean $age_{CONpassive}$ = 72.2 ± 7.2 Mean age_{EXP} = 74.1 ± 7.0	Virtual reality balance training 8 weeks: 3-times per week (40 min/trial)	CON motor = Traditional balance training CON passive = Passive group (only pre- and post-intervention assessment) 8 weeks: 3-times per week (40 min/trial)	Gait speed – ↑ CON motor and EXP group TUG – ↑ CON motor and EXP group
Gallardo-Meza et al. (2022)	*N* = 72 (CON = 37, EXP = 35) Mean $age_{CON=}$ 69.2 ± 3.7 Mean age_{EXP} = 74.1 ± 7.0	Nintendo Wii training (Wii Fit Plus; Wii Balanceboard; Wii Nunchuk) 4 weeks: exergame:2-times per week (40 min/trial) + Recreational physical activity training: 1-time per week (40 min/trial)	Recreational physical activity training 4 weeks: 3-times per week (40 min/trial)	TUG – ↑ for EXP group
Lai et al. (2013)	*N* = 30 (CON = 15, EXP = 15) Mean $age_{CON=}$ 74.8 ± 4.7 Mean age_{EXP} = 70.6 ± 3.5	Interactive video game training (The Xavix Measured Step System) 6 weeks: 3-times per week (30 min/trial)	Passive group (only pre- and post-intervention assessment)	TUG – ↑ for EXP group BBS – ↑ for EXP group
Maillot et al. (2012)	*N* = 32 (CON = 16, EXP = 16) Mean $age_{CON=}$ 73.5 ± 3.0 Mean age_{EXP} = 73.5 ± 4.1	Nintendo Wii training (Wii Balanceboard; Wii Nunchuk) 12 weeks: 2-times per week (60 min/trial)	Passive group (only pre- and post-intervention assessment)	Gait speed ↑ for EXP group TUG ↑ for EXP group
Gschwind et al. (2015)	*N* = 153 (CON = 75, EXP = 78) Mean $age_{CON=}$ 74.7 ± 6.0 Mean age_{EXP} = 74.7 ± 6.7	Balance exergame training (iStoppFalls) + strength training 16 weeks: exergame: 2-times per week (60 min/trial) + strength training: 3-times per week (20 min/trial)	Passive group (only pre- and post-intervention assessment)	Gait speed (10 MWT) -DT; TUG (no improvement)
Gschwind et al. (2015)	*N* = 124 (CON = 61, $EXP_{kin=}$ 24, EXPsmt=39) Mean $age_{CON=}$ 80.2 ± 6.5 Mean $age_{EXP-kin=}$ 80.1 ± 6.3 Mean $age_{EXP-smt}$ = 82.5 ± 7.0	Home-based interventions of Kinect balance training or Step-mat-training (SMT) exergame Kinect: 16 weeks: exergame: 2-times per week (60 min/trial) + strength training: 3-times per week (20 min/trial) SMT: 16 weeks: exergame: 3-times per week (20 min/trial)	Passive group (only pre- and post-intervention assessment)	TUG (no improvement)
Rendon et al. (2012)	*N* = 34 (CON = 18, EXP = 16) Mean $age_{CON=}$ 83.3 ± 6.2 Mean age_{EXP} = 85.7 ± 4.3	Wii Fit balance training 6 weeks: 3-times per week (35–45 min/trial)	Passive group (only pre- and post-intervention assessment)	TUG (8 feet up and go) – ↑ for EXP group
Franco et al. (2012)	*N* = 32 (CON motor = 11, CON passive = 10, EXP = 11) Mean $age_{CONmotor}$ = 77.9 ± 6.9 Mean $age_{CONpassive}$ = 76.9 ± 6.3 Mean age_{EXP} = 79.8 ± 4.7	Wii Fit balance group 3 weeks: 2-times per week (10–15 min/trial)	CON motor = Matter of balance group CON passive = Passive group (only pre- and post-intervention assessment) 3 weeks: 2-times per week (30–45 min/trial)	BBS – ↑ for CON motor and EXP group
Pluchino et al. (2012)	*N* = 26 (CON = 14, EXP = 12) Mean $age_{CON=}$ 76.0 ± 7.7 Mean age_{EXP} = 70.7 ± 8.5	Video game balance board training 8 weeks: 2-times per week (60 min/trial)	Balance training program 8 weeks: 2-times per week (60 min/trial)	TUG (no improvement)
Jorgensen et al. (2013)	*N* = 58 (CON = 30, EXP = 28) Mean $age_{CON=}$ 73.7 ± 6.1 Mean age_{EXP} = 75.9 ± 5.7	Biofeedback-based Nintendo Wii training 10 weeks: 2-times per week (30-40 min/trial)	Ethylene vinyl acetate copolymer insoles	TUG – ↑ for EXP group
Park et al. (2015)	*N* = 24 (CON = 12, EXP = 12) Mean $age_{CON=}$ 65.2 ± 7.9 Mean age_{EXP} = 66.5 ± 8.1	Virtual reality training (Wii Fit balance exercise) 8 weeks: 3-times per week (30 min/trial)	Ball game training 8 weeks: 3-times per week (30 min/trial)	TUG – ↑ for CON and EXP group
Kwok and Pua (2016)	*N* = 80 (CON = 40, EXP = 40) Mean $age_{CON=}$ 70.5 ± 6.7 Mean age_{EXP} = 69.8 ± 7.5	Wii exercise program 12 weeks: 1-times per week (60 min/trial)	Standard Gym-based exercise 12 weeks: 1-times per week (60 min/trial)	TUG – ↑ for CON and EXP group Gait speed (6MWD) – ↑ for CON and EXP group

(Continued)

TABLE 5 | Continued

Study	Sample description	Experimental design and duration of trial period	Control design and duration of trial period	Outcomes and results
Yesilyaprak et al. (2016)	$N = 18$ (CON = 11, EXP = 7) Mean $age_{CON=}$ 70.1 ± 4.0 Mean age_{EXP} = 73.1 ± 4.5	Virtual reality balance training (BTS NIRVANA VR Interactive System) 6 weeks: 3-times per week (45–60 min/trial)	Conventional balance training 6 weeks: 3-times per week (45-60 min/trial)	BBS – ↑ for CON and EXP group TUG – ↑ for CON and EXP group
Eggenberger et al. (2016)	$N = 33$ (CON = 14, EXP = 19) Mean $age_{CON=}$ 77.8 ± 7.4 Mean age_{EXP} = 72.8 ± 5.9	Interactive cognitive-motor video game dancing 8 weeks: 3-times per week (30 min/trial)	Balance and stretching training 8 weeks: 3-times per week (30 min/trial)	Gait speed (4MWT) (no improvement)
Padala et al. (2012)	$N = 22$ (CON = 11, EXP = 11) Mean $age_{CON=}$ 81.6 ± 5.2 Mean age_{EXP} = 79.3 ± 9.8	Wii Fit training 8 weeks: 5-times per week (30 min/trial)	Walking training 8 weeks: 5-times per week (30 min/trial)	BBS – ↑ for CON and EXP group TUG – ↑ CON group
Lee et al. (2018)	$N = 40$ (CON = 21, EXP = 19) Mean $age_{CON=}$ 75.7 ± 4.9 Mean age_{EXP} = 76.2 ± 4.6	Virtual reality training program 6 weeks: 2-times per week (60 min/trial)	Passive group (only pre- and post-intervention assessment)	BBS – ↑ for EXP group TUG – ↑ for EXP group
Nagano et al. (2016)	$N = 39$ (CON = 19, EXP = 20) Mean $age_{CON\,=}$ 72.0 ± 5.0 Mean age_{EXP} = 72.0 ± 5.0	Stepping mat exergame 12 weeks: 2-times per week (15 min/trial)	Passive group (only pre- and post-intervention assessment)	Gait speed (10 MWT) TUG – ↑ for EXP group
Yoo et al. (2013)	$N = 21$ (CON = 11, EXP = 10) Mean $age_{CON\,=}$ 75.6 ± 5.6 Mean age_{EXP} = 72.9 ± 3.4	Augmented reality-based Otago exercise 12 weeks: 3-times per week (60 min/trial)	Otago exercise group 12 weeks: 3-times per week (60 min/trial)	Gait speed – ↑ for CON and EXP group BBS – ↑ for CON and EXP group
Lee et al. (2015)	$N = 54$ (CON = 28, EXP = 26) Mean $age_{CON=}$ 67.7 ± 4.3 Mean age_{EXP} = 68.8 ± 4.6	Individualized feedback-based virtual reality exercise 8 weeks: 3-times per week (60 min/trial)	Postural, balance, functional, lower body coordination, and lower body strength exercises 8 weeks: 3-times per week (60 min/trial)	8FUGT – ↑ for CON and EXP group

training alone is an important point to discuss. The finding is in line with one other systematic review (Gavelin et al., 2021) showing that the addition of cognitive training to physical exercise does not reduce physical efficacy of the training, and exergaming was only superior to passive control for both physical and cognitive outcomes. However, this review also found that motor-cognitive training is likely to be most effective for cognition.

The effect size of the overall improvement in gait speed under a single-task conditions was small, with high statistical heterogeneity between studies. Because of the great heterogeneity in the methods and measurements of the studies, more studies within each subgroup would be needed to draw definitive conclusions. When planning future motor-cognitive interventions, overall effectiveness is important and a deeper understanding of causation is needed (e.g., type and design of intervention, quality of research conducted). There were 27 studies in which motor-cognitive intervention had a positive effect and 14 studies in which motor-cognitive intervention had a negative effect. Among the studies with the positive effect, the highest effect of intervention had the study by Sadeghi et al. (2021) (quality score = 6/11, see **Table 2**). The experimental design of this study involved a motor-cognitive intervention with visual context displayed on a PC, a confirmed human-computer interaction with tasks performed dynamically. The effect of an intervention study conducted by Jardim et al. (2021) (quality score = 6/11), in which participants performed aerobic, resistance, and stretching training while simultaneously solving cognitive tasks, was similarly high. The third largest effect was in the study by Pothier et al. (2018) (quality score = 4/11), where participants in addition to the aerobic and resistance training, performed cognitive training on a PC. Taken together, analysis of studies with larger effect sizes did not identify any pure trends that could currently provide an answer to the most effective designs of motor-cognitive interventions.

Finally, an additional analysis was performed excluding the study by Eggenberger et al. (2016) due to poor quality (PEDro score ≤ 3). The exclusion of the study did not affect the final conclusion of the results, as the additional calculations only confirmed the results reported above.

Gait Speed Under a Dual-Task Condition

We included twenty studies in the meta-analysis to evaluate the effect of a motor-cognitive intervention on gait speed under dual-task conditions, which yielded a non-significant effect. Regarding the quality (assessed by the PEDro scale) of the included studies, 6 studies were of "good quality" and 5 studies were of "fair quality". Heterogeneity was moderate (82%), and the dual-task assessment methods varied considerably. When interpreting our non-significant results on gait speed under dual-task conditions, it should also be considered that dual-task walking used different cognitive tasks and were combined into one effect size (e.g., walking with n-back task, verbal fluency task, backward couniting, Go/No Go task). Therefore, future studies should investigate this effect considering different subcategories of cognition as a secondary task.

Timed Up and Go Test Outcomes

We found that motor-cognitive intervention has a small positive effect on TUG performance for healthy individuals. Moreover, our analysis showed that motor-cognitive intervention is more effective than other conventional interventions in improving the TUG test, but the type of motor-cognitive intervention is not a moderating factor for a positive effect.

The overall effect size was small, with the majority of included studies showing a positive effect of motor-cognitive intervention on TUG test. We included 41 studies, of which 33 had a positive effect size and 8 had a negative effect size. The three interventions related to TUG performance with high effect sizes differed in the type of motor-cognitive intervention as well as in the study quality ratings; one study conducted motor-cognitive training with an additional cognitive task (Jardim et al., 2021; quality score = 6/11). The experimental design included the simultaneous performance of aerobic, resistance, and stretching training, in addition to the performance of various cognitive tasks. Two studies conducted motor-cognitive training with an incorporated cognitive task (Sápi et al., 2019, quality score = 3/11, Kinect balance training; Sadeghi et al., 2021, quality score = 6/11, balance training in virtual reality). On the other hand, the highest negative effect was found by Medeiros et al. (2018) (quality score = 7/11), but it was still only a small negative effect. In the latter study, participants in the experimental group performed a combination of aerobic, flexibility, strength, and balance training while completing a cognitive task. The authors explained the negative effect by the type of the sample (participants had exercised before the intervention) and the relatively short duration of the intervention (12 weeks). Similar to gait speed under a single-task condition, no clear trend for the most effective design of motor-cognitive intervention can be derived for the TUG test.

In addition, the type of control group (passive vs. active) moderated the effects of motor-cognitive interventions, suggesting that motor-cognitive interventions are better able to improve multicomponent tasks of dynamic balance and mobility function as measured by the TUG. Indeed, both the passive and active control groups had a significant effect on the results. The effect of the passive control group was moderate, while the effect of the active control group was smaller, as expected (ES = small), but still statistically significant. Since TUG is a multicomponent test that examines balance, gait speed, and functional ability (Beauchet et al., 2011), it achieves higher ecological validity compared with less complex straight-line walking without an additional task. Motor-cognitive interventions could therefore be a promising strategy to improve dynamic balance and mobility in older adults. When performing a sub-analysis of different types of motor-cognitive interventions (although there was only a non-significant trend with $P = 0.064$), both the additional and incorporated interventions had a positive effect on TUG, but the sequential intervention did not. One possible explanation is that performing motor and cognitive tasks at different times (sequential motor-cognitive training) may not be as stimulating for improving complex movement tasks as performing these tasks simultaneously. In addition, Prosperini et al. (2021) conducted a meta-analysis in which they found that exergaming interventions can have a positive impact on the balance of people with neurological disorders. This study (Prosperini et al., 2021) was performed on a group of diseased older adults, and we cannot directly confirm our findings with the above-mentioned study, but related results may help us draw meaningful conclusions on this topic. That is, a motor-cognitive intervention with incorporated cognitive task or exergaming has already been shown to have a positive effect on the selected population.

In addition, our results were also confirmed by the exclusion of two studies that were considered to be of poor quality by the PEDro assessment (Bieryla and Dold, 2013; Sápi et al., 2019). Reanalysis confirmed a small but positive effect of motor-cognitive intervention on TUG scores and the effect of the intervention was still moderated by the control group.

Berg Balance Scale Outcomes

The 11 studies included in our meta-analysis showed a positive but small effect on Berg Balance Scale scores (BBS). Thus, motor-cognitive intervention may be beneficial for healthy older adults while improving BBS score, but no differences were found between control groups or type of intervention. All included studies had a positive effect on BBS. The highest effect of the intervention was found in the studies by Karahan et al. (2015) (quality score = 7/11) and Norouzi et al. (2019) (quality score = 8/11). Participants in the experimental group in the study by Karahan et al. (2015) performed exergaming training, where they exercised on the Xbox 360 Kinect. The control group participated in balance training at home. On the other hand, participants in the experimental group in the study by Norouzi et al. (2019) performed resistance training using an isokinetic training device while performing cognitive tasks. Considering that BBS evaluates static and dynamic balance, the possible explanation for the results in favor of the control group could be the implementation of conventional physical therapy, that is motor training. The conventional motor training may have a better effect on balance parameters (BBS) than walking or playing video games. In addition, the existing literature summarizing the effect of simultaneous motor-cognitive training with incorporated cognitive task is inconsistent; Howes et al. (2017) and Pacheco et al. (2020) concluded that exergaming can improve static balance measured with BBS, whereas Chen et al. (2021) did not reach this conclusion.

Limitations and Future Directions

There are also some limitations as well as future directions that should be mentioned. First, despite a high heterogeneity among motor-cognitive approaches in terms of the selected cognitive or motor task, duration, and frequency, we pooled and summarized the data for the meta-analysis. Second, our meta-analysis included participants with a mean age of 60 years, allowing for the possibility that some individuals in the studies were younger than this age. Third, the results of publication bias indicated the presence of bias in TUG and BBS outcomes. Future studies should focus on other aspects of functional mobility and examine the effectiveness of such motor-cognitive interventions on activities of daily living, such as navigating parks and grocery stores, ability to drive, and others. Finally, the current scarcity of literature on motor-cognitive interventions in specific disease populations may open new avenues of discussion for the implementation of such training. For example, technology-driven exergames with forms of extended reality (XR) that combine real and virtual environments and relate to human-machine interactions generated by computers and wearable technologies will provide services for remote monitoring, training, and telerehabilitation (Meulenberg et al., 2022). The nature of engagement in XR allows training and/or rehabilitation exercises to feel similar to physically performed actions, while seemingly being more engaging, motivating, and stimulating than conventional practice.

CONCLUSION

This systematic review and meta-analysis shows that conventional motor-cognitive interventions and technology-based exergames can improve performance-based measures of functional mobility in older adults. Our results show that motor-cognitive interventions can be effective, particularly in the multicomponent daily tasks that older adults encounter and that resemble the TUG test-mobility tasks of transferring from sitting to standing and walking, as well as balance tasks during walking, stopping, and turning. Because of substantial heterogeneity and the current limited availability of different types of interventions, conclusions should be drawn with caution. Further dose-response studies should be conducted to determine the appropriate training dose for this specific population. New insights into training design, as well as recent advances in immersive and wearable technology, offer a new perspective for implementing motor-cognitive interventions as more comprehensive training tools to improve functional mobility in the elderly and increase their effectiveness.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

KT and UM designed the research. KT, LŠ, and AP performed the data extraction and performed the meta-analysis. KT, EB, and UM drafted the manuscript. KT, LŠ, EB, AP, and UM edited and revised the manuscript. All authors approved the final version of the manuscript.

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SUPPLEMENTARY MATERIAL

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Visuomotor Adaptation of Lower Extremity Movements During Virtual Ball-Kicking Task

Mai Moriyama[1], *Motoki Kouzaki*[1,2] *and Shota Hagio*[1,2]*

[1] *Laboratory of Neurophysiology, Graduate School of Human and Environmental Studies, Kyoto University, Kyoto, Japan,*
[2] *Unit of Synergetic Studies for Space, Kyoto University, Kyoto, Japan*

Sophisticated soccer players can skillfully manipulate a ball with their feet depending on the external environment. This ability of goal-directed control in the lower limbs has not been fully elucidated, although upper limb movements have been studied extensively using motor adaptation tasks. The purpose of this study was to clarify how the goal-directed movements of the lower limbs is acquired by conducting an experiment of visuomotor adaptation in ball-kicking movements. In this study, healthy young participants with and without experience playing soccer or futsal performed ball-kicking movements. They were instructed to move a cursor representing the right foot position and shoot a virtual ball to a target on a display in front of them. During the learning trials, the trajectories of the virtual ball were rotated by 15° either clockwise or counterclockwise relative to the actual ball direction. As a result, participants adapted their lower limb movements to novel visuomotor perturbation regardless of the soccer playing experience, and changed their whole trajectories not just the kicking position during adaptation. These results indicate that the goal-directed lower limb movements can be adapted to the novel environment. Moreover, it was suggested that fundamental structure of visuomotor adaptation is common between goal-directed movements in the upper and lower limbs.

Keywords: lower limb movement, motor learning, visuomotor rotation, goal-directed movement, virtual reality

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Steven van Andel,
University of Innsbruck, Austria

Reviewed by:
Jonathan Tsay,
University of California, Berkeley, United States
Katinka Van Der Kooij,
VU Amsterdam, Netherlands

Correspondence:
Shota Hagio
hagio.shota.3r@kyoto-u.ac.jp

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INTRODUCTION

Sophisticated football players can run across the playing field while skillfully manipulating the ball with their feet. Lower extremities play a primary role in controlling upright standing or locomotion that stabilizes or translates a body's center of mass (CoM) (Winter, 1995; Runge et al., 1999). In addition to the function involved with the CoM, the endpoint movements of the lower extremities can also be controlled toward a desired target, such as kicking a ball while playing soccer. Previous studies have demonstrated functional force control in the lower extremities to the desired multidirectional targets (Jacobs and Van Ingen Schenau, 1992; Hagio and Kouzaki, 2014). However, how the sensorimotor system learns goal-directed movements in the lower extremities is not fully understood.

Sensorimotor adaptation in the lower extremities has been studied with the split-belt adaptation task, where participants walk on belts moving at different speeds under each foot (Roemmich et al., 2016; Day et al., 2018). It was shown that lower-limb movements can be flexibly adapted to the novel environment. However, these studies investigated the adaptation of locomotion, not goal-directed movements in the lower extremity. Sensorimotor adaptation of goal-directed movements has been investigated using reaching tasks with the introduction of visuomotor or force-field perturbations (Shadmehr and Mussa-ivaldi, 1994; Krakauer et al., 2000). Since these tasks are upper extremity motor tasks, it is still unclear whether the process of adaptation in the goal-directed movements is common between the upper and lower extremity.

Goal-directed movements need appropriate sensorimotor transformation, i.e., transforming sensory input to the desired motor output, which is updated based on the experience of errors between the desired and actual movement (Wolpert et al., 1995; Krakauer et al., 1999; Wolpert and Ghahramani, 2000; Lalazar and Vaadia, 2008). Considering the differences in the characteristics of the upper and lower extremities, such as the moment of inertia of the segments (Winter, 2009) and the sensorimotor delay (Kandel et al., 2021), it is probable that the properties of the sensorimotor transformation are different between the upper and lower limb movements. Therefore, it is necessary to investigate the sensorimotor learning in the lower limb apart from the upper-limb motor learning.

The purpose in this study was to clarify how we adapt goal-directed movements in the lower limb. Here, we constructed a virtual ball-kicking task where the trajectory of the kicked ball was rotated relative to the actual trajectory. Thereby, we investigated the process of adaptation to the novel visuomotor environment in the lower limb control.

MATERIALS AND METHODS

Participants

Sixteen adults (10 males and 6 females) participated in this experiment. Half of the participants were "experts," who had played soccer or futsal for at least 3 years, and the others were untrained "novices." We recruited the experts and novices in order to clarify whether learning visuomotor perturbation with the lower limb requires familiarity with the lower limb control. Experts [6 males and 2 females, age = 22.6 ± 0.92 years, height = 169.0 ± 10.8 cm, weight = 62.8 ± 8.2 kg, mean ± standard deviation (SD)] had played soccer or futsal for at least 3 years (6.75 ± 2.82 years) in club activities at the college, high school, or junior high school level. The remaining 8 participants (4 males and 4 females, age = 22.5 ± 1.07 years, height = 170.0 ± 8.0 cm, weight = 64.0 ± 11.6 kg) were defined as novices who had never experienced both soccer and futsal. All participants were right-footed and manipulated their dominant leg. They gave informed consent, and the experimental procedures were in accordance with the Declaration of Helsinki and approved by the Ethics Committee for Human Experimentation at the Graduate School of Human and Environmental Studies, Kyoto University (19-H-25).

Experimental Setup

Participants stood on their left leg with their right hand on their hip and their left hand comfortably placed on a table (**Figure 1A**). The height of the table was adjusted depending on each participant. A 27-inch LCD monitor (60 Hz) was placed 1.5 m in front of the participants at eye level and displayed a target (10 cm × 50 cm), virtual ball (1 cm radius red circle), home position (0.5 cm radius green circle), and cursor (0.5 cm radius white circle) (**Figure 1B**). The target was displayed above the screen, the ball was 40 cm below the target, and the home position was 4 cm below the ball. The distance between the home position and the center of the virtual ball in reality was 50 cm. The horizontal right foot position was captured by the real-time motion tracking system used in our previous study (Hagio and Kouzaki, 2020). Trajectories of a rigid body created by three infrared reflective markers attached on the instep of the right foot were sampled at 100 Hz using the three-dimensional optical motion capture system (OptiTrack V100, Natural Point Inc., Corvallis, United States) with 12 cameras. The rigid body coordinates were streamed from Motive 2.0.2 software (Natural Point Inc., Oregon, United States) to MATLAB (R2019a, The MathWorks Inc., Natick, MA, United States) in real time and displayed in the 2-dimensional coordinates of a MATLAB figure as a white cursor (0.5 cm radius).

Virtual Ball-Kicking Task

Participants moved the cursor to hit the virtual ball displayed in the monitor toward the center of the forward target. The experimental task was assumed to be soccer ball kicking. They were instructed to move the cursor backward at first before hitting the virtual ball and then move toward the virtual ball. The trajectories of the virtual ball were determined depending on the cursor position and the velocity was immediately measured when the cursor hit the virtual ball. After the hitting, the virtual ball position, $(x,\ y)$, was translated following constant velocity linear motion:

$$\begin{bmatrix} x \\ y \end{bmatrix} = K \frac{m_{leg}}{m_{ball}} \begin{bmatrix} V_x \\ V_y \end{bmatrix} t$$

where V_x and V_y are the x- and y-components of the foot velocity transformed to the direction of the center of the ball, and m_{leg} and m_{ball} indicate the mass of the leg and the ball, respectively. t represents the time elapsed after the hitting. The body mass and mass of the leg were regarded as 50 kg and 16.1% of the body weight (Winter, 2009), respectively; m_{leg} was set as 8.05 kg. m_{ball} was determined to be 0.45 kg, corresponding to the weight of the official soccer ball. A constant parameter, K, was defined as 0.45 so that the ball moves naturally on the screen. Although the ball movement following constant velocity linear motion and no contact information between the ball and foot were different from the actual ball-kicking situation, the simple visuomotor task was intended to investigate the visuomotor control of the goal-directed lower limb movements.

Experimental Procedure

Before each trial, participants moved the cursor representing their right foot position to the home position on the monitor.

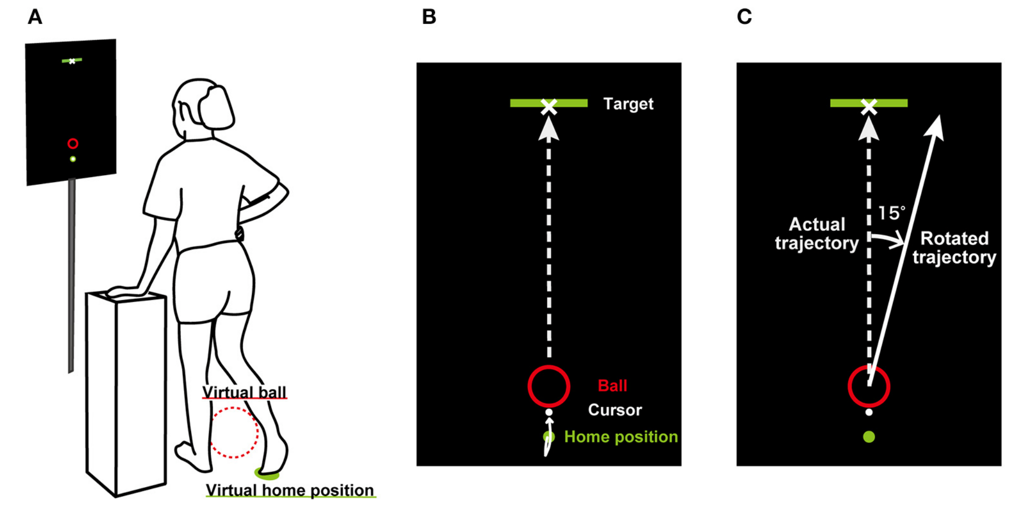

FIGURE 1 | Experimental setup. **(A)** shows how participants performed a ball-kicking task. They swung their right leg while standing with their right hand on their hip and their left hand comfortably placed on a table. They were asked to swing their right foot and kick a virtual ball in the display so that the virtual ball could hit the target. **(B)** illustrates the display shown in front of the participants. On the screen, the locations of the target, virtual ball, home position, and cursor on the horizontal plane were displayed. The virtual ball moved in constant velocity linear motion depending on the kicking position and the right foot velocity. **(C)** shows the rotated trajectory during the perturbation period.

After their right foot was held in the start position (within 2.5 cm in reality), a green rectangular target appeared. After 0.5–1.5 s, the target's color turned from green to magenta, and the home position disappeared, which was the cue that participants should initiate the movement to kick the virtual ball. After each trial, the velocity of the right foot after kicking the virtual ball was immediately shown on the screen. The participants were instructed to control the foot velocity to between 2.5 and 3.5 m/s.

This experiment was conducted for 2 days. The main experiment was performed on the second day, and these trials were used for analysis. On the first day, participants practiced the ball-kicking task 4–7 sets (40 trials per set) to get familiar with the task. There was a rest for 90 s after each set. After 160 trials, the practice was terminated when participants were able to hit the target and reduce the variability of ball direction, and the experimenter judged that the bias of ball direction had been stable during a set. The number of practice trials was decided by the same experimenter. On the second day, there were 400 trials (40 trials × 10 sets), and they were divided into three phases: baseline, perturbation, and washout periods. These phases consisted of 130, 160, and 110 trials, respectively. The length of each phase was determined based on pilot data so that the participants could adapt to the novel visuomotor environment; after-effects appeared after the perturbation period.

In the perturbation period, visuomotor perturbation was introduced without telling participants. Visuomotor perturbations have been used in reaching tasks, in which the cursor corresponding to the location of the subject's hand is rotated (Krakauer et al., 1999; McDougle et al., 2015). In the current study, the trajectories of the ball were rotated by 15° either clockwise or counterclockwise relative to the actual trajectories as follows (**Figure 1C**):

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

where x', y' corresponds to the rotated position of the ball; x, y corresponds to the actual position of the ball; and θ denotes the perturbation angle about the center of the ball at the start position equal to either 15° or −15°. The direction of visuomotor perturbation was counterbalanced across participants. All the experimental tasks were implemented using a custom-made MATLAB (R2019a, The MathWorks Inc., Natick, MA, United States) script.

Data Analysis for the Virtual Ball

The error on a given trial was calculated as the angular difference between a line from the starting position of the virtual ball to the target and a line in which the virtual ball moved. The mean error in the last 50 baseline trials was subtracted from the errors of all trials for each participant. In the case of the clockwise perturbation group, the errors were multiplied by −1 so that the positive error corresponded to the deviation of the virtual ball in the direction of the perturbation and vice versa. We quantified the mean error of the first 10 trials of the washout period as an aftereffect.

Outlier Analysis

Individual trials were excluded as outliers if the velocity of the right foot was smaller than 1.5 m/s or larger than 5.5 m/s. After that, the error thresholds of each participant at each phase (baseline, perturbation, and washout periods) of the task were determined as follows: in the baseline period, thresholds were defined as the mean ± 3 SD of errors during the last 50 baseline trials (= λ), while in the perturbation and washout periods, the predicted error (15°) was added to one of the thresholds (λ) of the side in which the effect of perturbation would appear [i.e., the direction where the error increased just after the perturbation was turned on (or off)]. If the error exceeded these thresholds, the data were removed. This resulted in the omission of <1.44% of trials on Day 2 (92 trials out of 6,400 trials).

Analysis of the Right Foot Trajectories

We focused on the trajectories of the cursor representing the right foot marker on the horizontal plane. The time series of the cursor position was filtered using a zero-lag, fourth-order Butterworth filter with a low-pass filter cutoff of 8 Hz. The onset of the data was defined as the moment when the movement exceeded 10% of peak velocity after leaving the starting position. The movement offset was immediately measured when the cursor contacted the virtual ball.

Statistics

All statistical tests were executed using functions in the Statistics Toolbox of MATLAB (R2019a). We performed a one-sample *t*-test for the size of the initial error in the washout period for each group (novices and experts). The difference was assumed to be statistically significant at an α threshold of 0.05.

RESULTS

Participants practiced the ball-kicking task on the first day. The mean absolute errors of the virtual ball and the variability of errors decreased through practice (**Supplementary Table 1**). On the second day, participants performed the main task consisting of 400 trials. The endpoint of the virtual ball and right-foot trajectories in the last 20 trials of the baseline period are shown for a representative expert (**Figure 2A**). The virtual ball position varied around the target, and the participant repeated a similar trajectory (**Figure 2A**). The virtual ball position and foot trajectories are also shown in 16 trials (every 10 trials) during the perturbation period when visuomotor rotation to a counterclockwise direction was applied for a representative expert (**Figure 2B**). After the perturbation was introduced, the virtual ball position deviated in the direction corresponding to the rotational perturbation and then gradually approached the target, which was accompanied by a change in the foot trajectories (**Figure 2B**).

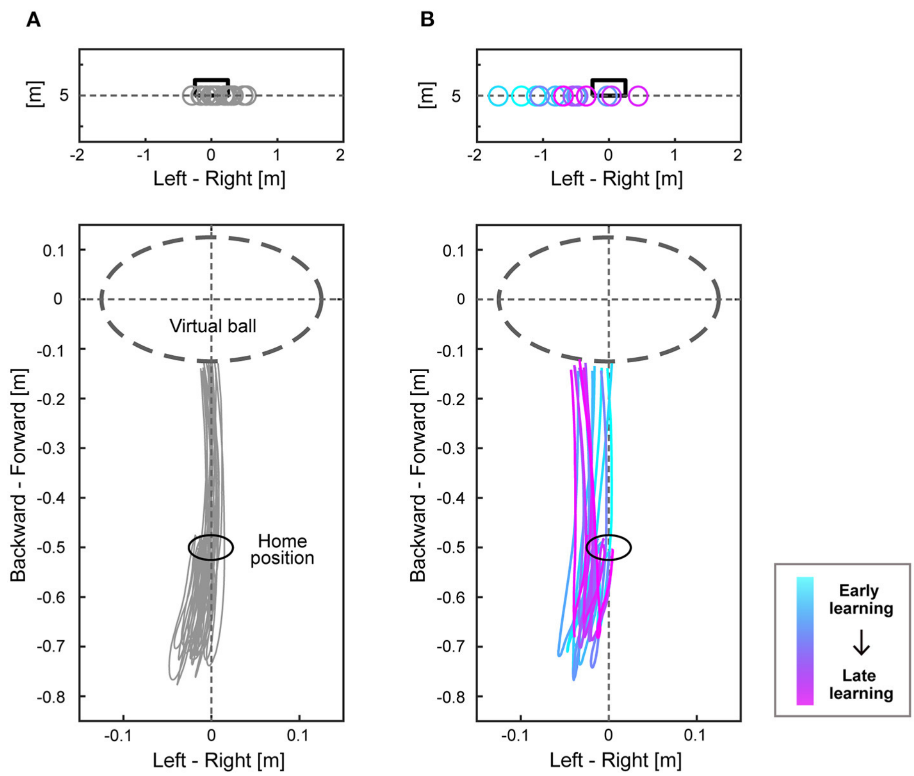

FIGURE 2 | Endpoints of the virtual ball and trajectories of the right foot. The upper figures of **(A,B)** show the endpoints of the virtual ball of a representative expert subject of the counterclockwise group. The black box represents the target, and each circle shows endpoints of the virtual ball at each trial. The lower figures of **(A,B)** show trajectories of the right foot on the horizontal plane when the participant swung their right foot backward from the home position and kicked the virtual ball. The dashed line circle represents the location of a virtual ball. **(A)** shows the results during the last 20 trials of the baseline period, and **(B)** shows each result of every 10 trials during the perturbation period (16 trajectories). The color changes from cyan to magenta as the trial proceeds.

Errors of the Virtual Ball

Figure 3 shows the mean errors in ball direction. Each individual participant's learning curve is shown in **Supplementary Figure 1**. Once the perturbation was introduced after the baseline period, the errors increased in the direction corresponding to the perturbation and then decreased by repeating the trials. Participants required about 100–120 trials to reduce the errors of the virtual ball. After the perturbation was turned off, errors were observed in the negative direction and then modified to the level equivalent to the baseline period. The size of the initial error in the washout period was significantly different from zero (novices, $-7.07 \pm 3.66^{\circ}$; $p < 0.001$; experts, $-6.84 \pm 2.75^{\circ}$; $p < 0.001$). This after effect indicates that participants adapted their lower limb movements to the novel visuomotor environment.

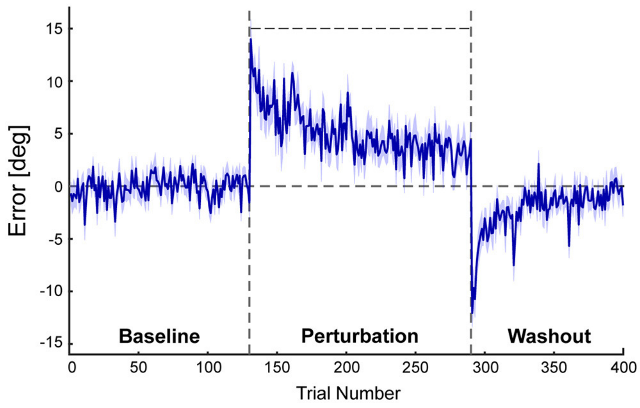

FIGURE 3 | Results of the errors between the center of the target and the endpoint of the virtual ball. This figure shows angular errors between the center of the target and the endpoint of the virtual ball. A positive error corresponds to the deviation of the virtual ball in the direction of the perturbation and vice versa. Blue lines represent the mean errors of all participants. The shaded area represents the standard error of the mean (SEM). Four hundred trials consisted of three phases: the baseline period (130 trials), perturbation period (160 trials), and washout period (110 trials). A horizontal line during the perturbation period (trial 131–290) indicates the perturbation of 15°.

Foot Trajectories

We next investigated the movement trajectories of the right foot. Each participant's trajectories of the right foot during the perturbation period are shown in **Supplementary Figure 2**. **Figure 4** shows the mean trajectories of the clockwise perturbation group during the perturbation and the washout period. During adaptation (**Figure 4A**), trajectories of the right foot were gradually changed from the baseline trajectory (a black line) to the direction corresponding to the perturbation so that participants could compensate for the increased error of the virtual ball position. Particularly, the foot movements were changed not only at the end of the trajectories, i.e., near the virtual ball, but for the entire trajectories both in backward and forward directions. After the perturbation was turned off, the trajectories gradually approached the baseline trajectory (**Figure 4B**).

DISCUSSION

In this study, we aimed to investigate how the goal-directed control of the lower limb is adapted. The results demonstrated that both the novices and experts can adapt their lower limb movements to novel visuomotor perturbation (**Figure 3**). Furthermore, the foot trajectories during adaptation showed that not only the trajectories near the kicking position but the whole trajectories were changed (**Figure 4**).

Participants in the current study were not told about the existence of the perturbation and told to hit the target with the virtual ball throughout the experiment. However, errors at the beginning of the washout period were significantly different from 0 (**Figure 3**). Moreover, participants couldn't immediately change their trajectories to the baseline trajectory after the perturbation was turned off (**Figure 4**). These results indicate that the current task elicited implicit adaptation. While, it should be noted that the washout trials may be contaminated with some explicit strategy. Participants in the present study were not restricted from aiming in other directions rather than toward the target (re-aiming strategy) so that the virtual ball could hit the target during the washout period. To isolate implicit adaptation, future studies should introduce other paradigms such as restricting participants from using explicit strategy or providing clamped visual feedback which is pre-determined and irrelevant to the task (Morehead et al., 2017; Tsay et al., 2020).

The visuomotor rotation in the current study presented a cursor representing veridical (not rotated) foot position and a rotated trajectory of the virtual ball. Accordingly, there was no sensory prediction error, a discrepancy between predicted and actual feedback of the effector, but a task error, which is a difference between actual performance and the task goal. This implies that implicit adaptation is induced by a discrepancy between predicted and actual feedback of the motor performance (predicted and perturbated trajectories of the virtual ball) rather than sensory prediction error (Ranjan and Smith, 2020). While, implicit adaptation has been thought to be elicited by sensory prediction error (Mazzoni and Krakauer, 2006; Shadmehr et al., 2010). Additionally, it has been shown that a visuomotor rotation task without sensory prediction error but with only task error does not induce trial-by-trial implicit adaptation (Tsay et al., 2022). Further studies are required to specifically investigate implicit adaptation without sensory prediction error.

During the perturbation period, the shape of the foot trajectory was changed from the baseline trajectory (**Figure 4**). Previous studies showed that the postadaptation trajectory in the visuomotor rotation task of the upper limb was the rotated trajectory of the baseline trajectory, resulting in a consistent shape before and after adaptation (Novick and Vaadia, 2011; Hirashima and Nozaki, 2012). It was also demonstrated that the directional tuning of muscle activity is rotated depending on the visuomotor perturbation (Gentner et al., 2013; De Marchis et al., 2018). However, such rotation did not appear to be applied to the visuomotor adaptation in the lower limb. Instead, the whole trajectories seemed to be more curved toward the direction of the perturbation (**Figure 4**). This might be due to the difference in

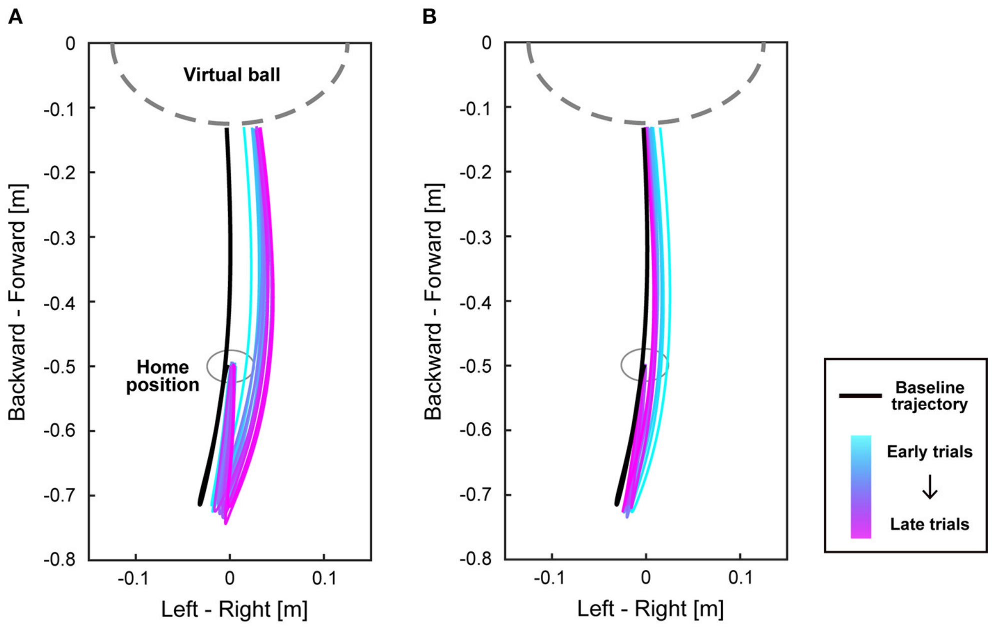

FIGURE 4 | Trajectories of the right foot during adaptation. **(A,B)** show the mean trajectories of the right foot on the horizontal plane from when participants started to move from the home position until their foot contacted the virtual ball. The black line represents the baseline trajectory of each group, and the colored lines show the mean trajectories of every 10 trials during the perturbation period **(A)** and the washout period **(B)** in the clockwise perturbation group. As the trials proceed, the color of the trajectory changes from cyan to magenta. The gray dashed line represents the location of a virtual ball.

the biomechanical properties or the degrees of freedom between the upper and lower limbs.

To our knowledge, this is the first study on visuomotor adaptation of goal-directed movement in the lower limb, although visuomotor adaptation of goal-directed movement in the upper limb has been studied for decades (Shadmehr and Mussa-ivaldi, 1994; Krakauer et al., 2000). There are many differences between the upper and lower limbs in motor control, such as the length of sensorimotor delay (Kandel et al., 2021) and the size of the moment of inertia of the segments (Winter, 2009), and moreover, standing posture must be maintained during lower-limb tasks. Indeed, such differences might be related to the fact that while the postadaptation trajectory of the visuomotor rotation task with the upper limb was rotated (Novick and Vaadia, 2011; Hirashima and Nozaki, 2012), the structure of the postadaptation trajectory in the lower limb was changed from the baseline trajectory rather than a simple rotation (**Figure 4**). Despite such dissimilarities, the time course of errors (**Figure 3**) was similar to previous studies on visuomotor learning of reaching movements (Mazzoni and Krakauer, 2006; Taylor et al., 2014; Singh et al., 2016), suggesting that the fundamental structure of visuomotor adaptation is common between goal-directed movements in the lower and upper limbs.

In the current study, we recruited the novices and experts to clarify whether learning visuomotor perturbation with the lower limb requires familiarity with the lower limb control. As a result, both novices and experts could adapt to the visuomotor rotation (**Figure 3**). Previous studies on motor learning in the upper limb movements have demonstrated that sensorimotor experience of task-related movements had an effect on motor learning of visuomotor rotation (Leukel et al., 2015; Kast and Leukel, 2016; Hewitson et al., 2020). It has been shown that experts rely on explicit strategies more than novices during adaptation (Leukel et al., 2015; Hewitson et al., 2020). Hence, it is possible that there was some difference in the contribution of explicit and implicit processes during the lower-limb adaptation between the novices and experts, which should be examined in future studies.

In conclusion, it was demonstrated that lower-limb movement can be adapted to the novel visuomotor environment. This finding suggests that the fundamental structure of visuomotor adaptation in goal-directed movements is universal regardless of the effector.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee for Human Experimentation at the Graduate School of Human and Environmental Studies, Kyoto University. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

MM, MK, and SH conceived the research, interpreted the data, revised the manuscript, and approved the final version to be published. MM and SH designed the experiment and collected and analyzed the data. MM prepared figures and drafted manuscript. SH edited the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2022.883656/full#supplementary-material

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Estimation of Joint Moments During Turning Maneuvers in Alpine Skiing Using a Three Dimensional Musculoskeletal Skier Model and a Forward Dynamics Optimization Framework

Dieter Heinrich[1]*, *Antonie J. Van den Bogert*[2] *and Werner Nachbauer*[1]

[1]*Department of Sport Science, University of Innsbruck, Innsbruck, Austria,* [2]*Department of Mechanical Engineering, Cleveland State University, Cleveland, OH, United States*

Edited by:
Thorsten Stein,
Karlsruhe Institute of Technology (KIT),
Germany

Reviewed by:
Paul Anthony Jones,
University of Salford, United Kingdom
Choongsoo S. Shin,
Sogang University, South Korea

***Correspondence:**
Dieter Heinrich
dieter.heinrich@uibk.ac.at

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In alpine skiing, estimation of the joint moments acting onto the skier is essential to quantify the loading of the skier during turning maneuvers. In the present study, a novel forward dynamics optimization framework is presented to estimate the joint moments acting onto the skier incorporating a three dimensional musculoskeletal model (53 kinematic degrees of freedom, 94 muscles). Kinematic data of a professional skier performing a turning maneuver were captured and used as input data to the optimization framework. In the optimization framework, the musculoskeletal model of the skier was applied to track the experimental data of a skier and to estimate the underlying joint moments of the skier at the hip, knee and ankle joints of the outside and inside leg as well as the lumbar joint. During the turning maneuver the speed of the skier was about 14 m/s with a minimum turn radius of about 16 m. The highest joint moments were observed at the lumbar joint with a maximum of 1.88 Nm/kg for lumbar extension. At the outside leg, the highest joint moments corresponded to the hip extension moment with 1.27 Nm/kg, the knee extension moment with 1.02 Nm/kg and the ankle plantarflexion moment with 0.85 Nm/kg. Compared to the classical inverse dynamics analysis, the present framework has four major advantages. First, using a forward dynamic optimization framework the underlying kinematics of the skier as well as the corresponding ground reaction forces are dynamically consistent. Second, the present framework can cope with incomplete data (i.e., without ground reaction force data). Third, the computation of the joint moments is less sensitive to errors in the measurement data. Fourth, the computed joint moments are constrained to stay within the physiological limits defined by the musculoskeletal model.

Keywords: skiing, turning maneuver, joint moments, forward dynamics, optimal, control, data tracking, musculoskeletal model

1 INTRODUCTION

In alpine skiing, field experiments in the natural environment (i.e., on the ski slope) are essential to analyze the movement of the skier regarding performance characteristics or for the purpose of injury prevention. While performance analyses primarily focus on kinematic characteristics of the skier such as the trajectory of the center of mass, the skier's velocity and/or the path length of a turning maneuver (e.g., Federolf, 2012; Spörri et al., 2012; Gilgien et al., 2015; Fasel et al., 2018a), kinetic characteristics such as the joint moments at the lumbar, hip, knee and ankle joints of the skier or the ground reaction forces are the main focus in the context of injury prevention (e.g., Stricker et al., 2010; Klous et al., 2012; Lee et al., 2017; Spörri et al., 2018; Meyer et al., 2019).

Focusing on injury prevention, inverse dynamics is the preferred approach to estimate the joint moments acting on a skier during turning maneuvers (e.g., van den Bogert et al., 1999; Klous et al., 2012, 2014; Hirose et al., 2013; Lee et al., 2017). An inverse dynamics analysis is typically based on kinematic data of the body segments of the skier as well as measurement data of external forces (i.e., ground reaction forces) as input and provides the net joint moments of the skier as output (Winter 2009). The loading of the knee joint is of high interest, since most serious injuries in recreational skiing (Posch et al., 2021) and competitive alpine skiing are located at the knee (Haaland et al., 2016; Barth et al., 2021). Inverse dynamics is computationally inexpensive, straightforward and available in several software packages such as OpenSim or Anybody. However, it has some important limitations. First, in an inverse dynamics analysis the kinematics and ground reaction forces are dynamically not consistent (Fluit et al., 2014). This inconsistency arises due to measurement errors of the kinematics and ground reaction forces as well as differences between the biomechanical model used in the inverse dynamics analysis and the real physical system (Hatze, 2002) and introduces errors in the computation of the joint moments (Faber et al., 2018). Second, an inverse dynamics analysis requires double differentiation of the segment kinematics, which amplifies errors in the measurement data. Consequently, inverse dynamics is highly sensitive to measurement errors (Cahouët et al., 2002; Pàmies-Vilà et al., 2012). Third, the computed joint torques are not constrained to stay within physiological limits (Bailly et al., 2021). The main reason is that muscle characteristics such as the maximum isometric force, the force-length relationship, the force-velocity relationship and the activation dynamics are not taken into account in the inverse dynamics analysis of the joint moments. Consequently, the estimated joint moments might be unrealistic high and physiologically not plausible (Bailly et al., 2021).

These limitations of inverse dynamics analysis may have affected previous studies in alpine skiing estimating joint moments during turning maneuvers. Hirose et al. (2013), for example, computed the joint moments at the lower extremities during a carving turn using an inverse dynamics analysis that was based on kinematic data obtained by an IMU based system and measured ground reaction forces between the ski boot and ski. They reported a peak external hip flexion moment of about 900 Nm, which is about a factor of 2.5 above the maximum voluntary hip joint torque reported in the study of Anderson et al. (2007) for the age group 19 to 25. Furthermore, Klous et al. (2012), computed knee extension moments up to 8.35 Nm/kg and 4.07 Nm/kg for a skidded and a carved turn, respectively. Although the speed of the skier was relatively low in the carved turn (v = 13.9 m/s) and the skidded turn (v = 10.4 m/s), the reported peak knee flexion moments exceeded in turn the maximum voluntary joint torques derived by Anderson et al. (2007). The inverse dynamics analysis incorporated kinematic data captured by a multi-camera system and ground reaction force measured by custom-built mobile force platforms mounted between the ski binding and the ski. In addition, Klous et al. (2012) reported peak external knee abduction moments, which are about a factor of three higher than the assumed injury threshold of 125 Nm valgus moment in the study of McLean et al. (2008), although they did not investigate an injury prone situation. Thus, the reported peak joint moments in these studies are likely to be error prone and unrealistic high.

As an alternative to inverse dynamics, recent advances in forward dynamics methods opened up new opportunities (Erdemir et al., 2007). Specifically, given a musculoskeletal model, forward dynamics optimization such as forward dynamics assisted data tracking offer the possibility to estimate dynamically consistent kinematics and ground reaction forces as well as joint torques and muscle forces (Nitschke et al., 2020). In addition, these methods are less sensitive to errors in the measurement data and allow to incorporate the force generating muscle properties such as the maximum isometric force, the force-length relationship, the force-velocity relationship and the muscle activation dynamics (Erdemir et al., 2007).

In alpine skiing, only a few studies applied a musculoskeletal simulation model in combination with forward dynamics optimization to estimate consistent joint kinematics and ground reaction forces, joint torques and muscle forces (e.g., Gerritsen et al., 1996; Heinrich et al., 2014, 2018). However, all of these studies incorporated a two dimensional model of an alpine skier, which was constrained to the sagittal plane and applied to analyze jump landing maneuvers in downhill skiing. Analyzing turning maneuvers, however, requires a three dimensional skier model. To the authors' knowledge, no three dimensional musculoskeletal skier model has been developed. Therefore, the first objective of the present study was to develop a three dimensional musculoskeletal model of an alpine skier capable of simulating turning maneuvers. The second objective was to apply the musculoskeletal skier model in combination with a forward dynamics optimization framework to estimate dynamically consistent kinematics, ground reaction forces and joint moments during a turning maneuver. The estimation of the joint moments was constrained such that computed joint torques stayed within physiological limits imposed by the musculoskeletal model.

2 MATERIALS AND METHODS

2.1 Musculoskeletal Skier Model

We developed a three dimensional musculoskeletal model of an alpine skier with two skis and 53 degrees of freedom (19 for the

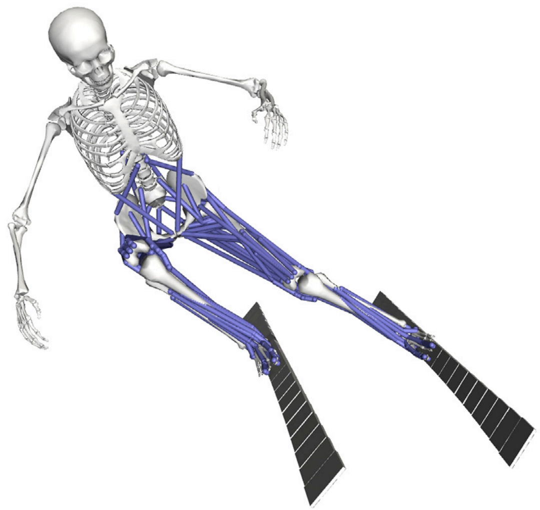

FIGURE 1 | Three dimensional musculoskeletal model of the skier with two skis, 53 kinematic degrees of freedom (19 for the skier and 17 for each ski) and 94 muscles visualized in OpenSim (Delp et al., 2007). The subtalar and mtp joints were locked because of the skier's ski boots, which allowed only plantarflexion and dorsiflexion at the ankle joints.

skier and 17 for each ski) to simulate turning maneuvers in alpine skiing (**Figure 1**). The skeletal model of the skier consisted of 20 rigid segments and was derived from the full-body OpenSim model of Hamner et al. (2010). At each lower extremity the subtalar and mtp joints were locked because of the skier's ski boot, which allows only plantarflexion and dorsiflexion at the ankle joint. The restraining effect of the ski boot was represented by a passive moment at the ankle joint incorporating the non-linear relation between the boot-induced moment and the ankle joint angle (Eberle et al., 2017). To increase computational speed the position of the arms of the skier was locked in a typical position and the mass of the ski poles was neglected. In total, the skier model had 19 degrees of freedom (6 between pelvis and ground; 3, 1, and 1 at each hip, knee and ankle, respectively; 3 at the lumbar joint between trunk and pelvis).

Each ski was discretized into 18 rigid segments (7 rear segments, 1 center segment and 10 front segments) connected by revolute joints. Mass and inertia properties of the ski segments were derived form measurement data of a competitive giant slalom ski. The length of the ski was 2.02 m with a sidecut radius of 32 m and a mass of 2.1 kg. The center segment was firmly affixed to the foot-ski boot segment of the skier model. Rotational spring-damper elements were attached to the revolute joints to incorporate stiffness and damping properties of the skis (Heinrich et al., 2014). Stiffness and damping parameters were derived from laboratory measurements of bending deflection and bending vibration (Mössner et al., 2014). Torsional twist of the skis was neglected because it was shown to be low during turning maneuvers (Yoneyama et al., 2008).

The motion of the skier was actuated by 94 muscles (43 per leg and eight actuating the lumbar joint). The muscle model was based on the OpenSim model of Catelli et al. (2019), since deep squatting and high hip flexion are often encountered during turning maneuvers. In the OpenSim model of Catelli et al. (2019), 80 muscles were includes (40 per leg) actuating the joints of both legs only. To actuate the lumbar joint additionally, we added eight muscles (2 × erector spinae, rectus abdominus, external obliques, internal obliques) to the skier model (Harris et al., 2017). Furthermore, we added three hip muscles (gemelli, pectineus, quadratus femoris) to each leg to increase hip muscle strength based on the musculoskeletal model presented in Harris et al. (2017) focusing on hip musculature.

Muscle activation dynamics was assumed as a first-order process (He, 1991) and models the change in muscle activation as a function of the current active state and the neural excitation of the muscle. The corresponding time constants for muscle activation and deactivation were set to 10 and 40 ms, respectively (Zajac, 1989; Nitschke et al., 2020). Muscle contraction dynamics was modeled in analogy to Nitschke et al. (2020) assuming a three-element Hill-type muscle model, which incorporates the force-length-velocity characteristics of the muscle. Contraction dynamics was formulated in implicit form, which was shown to result in better convergence and increased computational speed (van den Bogert et al., 2011; De Groote et al., 2016).

The dynamics of the whole musculoskeletal skier model was given by the multibody dynamics of the skier and skis, the muscle activation dynamics and the muscle contraction dynamics. The dynamics was formulated in implicit form (van den Bogert et al., 2011) as

$$f(x, \dot{x}, u) = 0 \quad (1)$$

where x denotes the states of the musculoskeletal skier model, $\dot{x}$ the time derivative of the states and u the controls of the musculoskeletal skier model. Specifically, the states x of the musculoskeletal skier model were represented by the degrees of freedom and their derivatives of the multibody model of the skier and skis, the projected length of the muscle fibers (=length of the contractile element in the Hill muscle model) and the muscle activations; the controls u of the musculoskeletal skier model were represented by the neural muscle excitations of the muscles (van den Bogert et al., 2011).

2.2 Ski-Snow Contact Model

We modeled the ski-snow contact using three types of forces acting on each segment of both skis (Mössner et al., 2014). First, we applied a penetration force F_p acting normal to the snow surface. The penetration force was based on an elastic force penetration relation and depended on the penetration depth and speed of the edge of the ski segment orthogonal to the snow surface as well as the edging angle of the ski. The edging angle was defined as the angle between the base surface of the ski segment and the snow surface. Second, we applied a shear force F_s acting orthogonal to the ski edge and parallel to the snow surface. The shear force provided resistance against lateral shearing and depended on the penetration depth of the ski edge. Finally, we applied a frictional force F_f acting antiparallel to the segment's velocity with a constant friction coefficient $\mu = 0.1$ (Heinrich et al., 2014; Mössner et al., 2014).

2.3 Experimental Data

To analyze a turning maneuver with the present musculoskeletal model we took measurement data collected by our working group in a previous study (Filippi Oberegger, 2011) where a professional skiing instructor performed a turn to the right with the same giant slalom skies implemented in the musculoskeletal skier model. The movement of the skier was captured by a multi-camera system consisting of three cameras and a frequency of 50 Hz. In a post-processing step 23 landmarks of the skier were manually digitized and the three dimensional coordinates were reconstructed using the direct linear transformation (DLT) algorithm. Given the 23 landmarks we used OpenSim to scale the skier model and used the inverse kinematics tool to compute the kinematics of the skier (i.e., joint angles of skier at the inside and outside leg, joint angles at the lumbar joint and the translation and orientation of the pelvis segment of the skier).

2.4 Optimization Framework

Given the musculoskeletal skier model, we used a forward dynamics optimization framework to simulate the movement of the skier, track the experimental data of the skier during the turning maneuver and to compute the joint moments of the skier. Specifically, we formulated a corresponding optimal control problem (i.e., tracking problem). The task of the optimal control problem was to find the states x and controls u of the musculoskeletal skier model such that a given objective function J is minimized (van den Bogert et al., 2011). Specifically, we used the following objective function

$$J = \frac{1}{T}\int_0^T \underbrace{w_1\|err_q\|_2^2}_{tracking\ error} + \underbrace{w_2\left(\sum_{i=1}^{nmus} a_i^2\right)}_{muscle\ effort} + \underbrace{w_3\left(\|\dot{x}\|_2^2 + \|\dot{u}\|_2^2\right)}_{regularization}$$

including a tracking error term, a muscle effort term and a regularization term. Simulation time is denoted by T, $\| - \|_2$ denotes the Euclidean norm, $nmus$ the number of muscles and w_1, w_2 and w_3 are weighting factors.

The first term in the objective function corresponded to the tracking error where err_q denotes the deviation of the degrees of freedom of the skier model (i.e., pelvic translation and rotation, joint angles at the lumbar, hip, knee and ankle joints) and the corresponding measurement data. The second term in the objective function corresponded to muscle effort and was used to resolve muscle redundancy (having more muscles than degrees of freedom). In the literature several criteria have been suggested (Erdemir et al., 2007). One common criterion is to use muscle activation a squared as a surrogate for muscle effort. This criterion has been used in a number of studies involving dynamic movement tasks such as jump landing (Laughlin et al., 2011), squatting (Catelli et al., 2019) or cutting (Weinhandl and O'Connor, 2017). Finally, a small regularization term was added with a small weight factor w_3 to enhance convergence by minimizing the derivatives of the states x and controls u (Nitschke et al., 2020).

The optimal control problem was subjected to constraints due to the dynamics of the musculoskeletal skier model (i.e., muscle activation and contraction dynamics and multibody dynamics of the skier model) as well as lower and upper bounds on the states x and controls u (van den Bogert et al., 2011; Nitschke et al., 2020).

2.5 Model Implementation and Numerical Solution

Solving an optimal control problem is computationally challenging. Recently, however, several efficient computational frameworks have been developed for solving dynamic optimization problems (e.g., Falisse et al., 2019; Nitschke et al., 2020). Similar to the approach of Nitschke et al. (2020) we implemented and solved the optimal control problem in an efficient way. We used MotionGenesis (Motion Genesis LLC, Menlo Park, CA, United States) to generate the equations of motion for the multibody dynamics of the skier model. The equations of motion were exported as C-code and imported in MATLAB *via* the MEX interface. In MATLAB we fused the equations for the multibody dynamics and the muscle contraction and activation dynamics and formulated the optimal control problem (i.e., tracking problem). To solve the optimal control problem, we transformed it into a constrained nonlinear programming problem (NLP) using direct collocation and the implicit Euler formula (van den Bogert et al., 2011). To increase computational speed, we provided analytical derivatives of the objective function and constraints to the NLP solver IPOPT (Nitschke et al., 2020).

2.6 Data Analysis

To evaluate the simulation of the turning maneuvers and the associated tracking error, we first calculated the root mean squared difference (RMSD) between the joint angles of the skier derived from the measurement data and the corresponding joint angles of the skier in the simulation. Second, we compared the track of the skier where we used the ankle joint centers of the outside and inside leg as reference points (Supej et al., 2020). Finally, we computed the RMSD between the measured and simulated speed of the skier during the turning maneuver. In the data analysis, we focused on the steering phase of the turning maneuvers, where the skier is subjected to the highest loads (Klous et al., 2012, 2014). Similar to the recent study of Supej et al. (2020), we defined the beginning and end of steering phase when the turn radius of the skier was below the side cut radius of the ski (R = 32 m). After the evaluation we computed the joint moments at the hip, knee and ankle joint of the outside and inside leg as well as the lumbar joint of the skier. Joint moments were represented as internal joint moments and hip flexion, adduction and internal rotation, knee extension and ankle dorsiflexion moments were denoted as positive. To analyze the loading of the knee joints in more detail, we further computed the full 6-DOF intersegmental joint moments and forces at the knee of the outside and inside leg (van den Bogert et al., 2013), respectively, solving the Newton-Euler equations consecutively starting at the ski segments to the shank segment. Since intersegmental joint forces are not the total forces at joint and have limited utility on their own (Derrick et al., 2020), we focused on the analysis of the intersegmental knee joint moments. The intersegmental knee joint moments and forces were represented

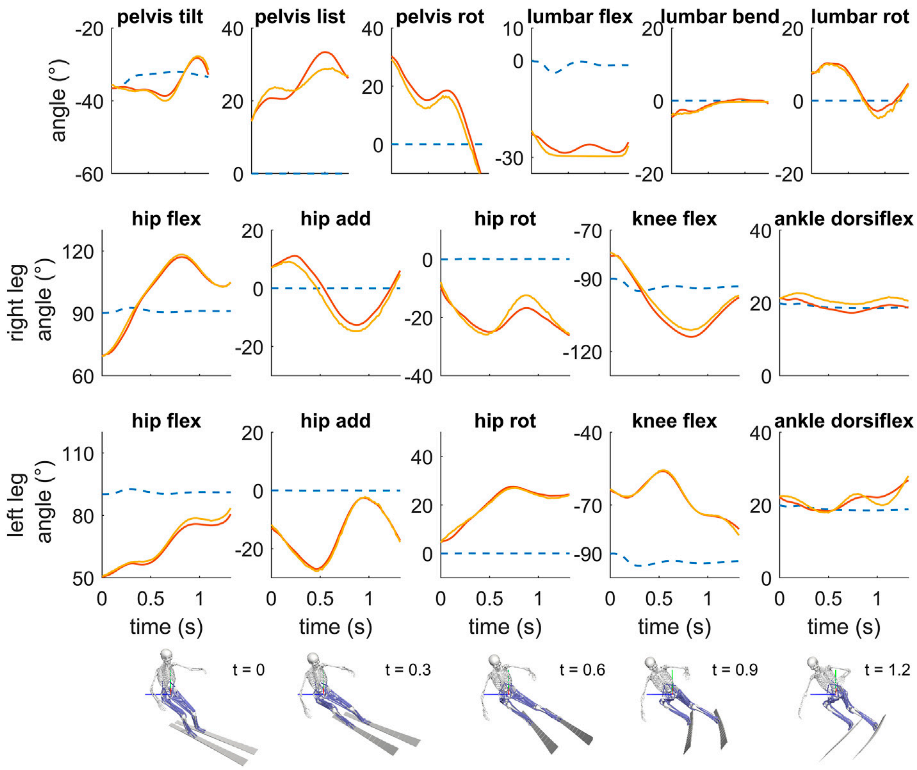

FIGURE 2 | Comparison of the optimized kinematics of the skier (red) during the turning simulation and the corresponding measured kinematic data (yellow). Kinematic data refer to the orientation of the pelvis (tilt, list, rotation) and the joint angles at the lumbar joint (flexion, lateral bending, rotation), hip joint (flexion, adduction, internal rotation), knee joint (flexion) and ankle joint (dorsiflexion). The blue dotted lines represent the kinematics of a straight schussing maneuver, which was used as initial guess in the optimization framework.

in the local coordinate system of the shank; the x-axis, y-axis and z-axis referred to the anterior-posterior, superior-inferior and medial-lateral direction.

3 RESULTS

3.1 Kinematics

In the forward dynamics optimization framework, the turning maneuver could be successfully simulated (an animation of the simulated turning maneuver is provided as **Supplementary Material**) in about 35 min of computational time on a single core of a workstation (Thinkstation 330, 3.5 GHz E-2146 CPU). In the simulation, the musculoskeletal skier model was able to track the measured kinematic data closely (**Figure 2**). Specifically, the RMSD between the measured joint angles and the joint angles obtained by the musculoskeletal skier model were in the range from 0.50 to 2.72° (**Table 1**). The lowest differences were observed for lumbar bending and knee flexion at the outside left leg; the highest differences were observed for pelvis list and hip adduction at the inside right leg.

In addition, the simulated track of the skier and the speed of the skier were in good agreement with the measurement data At the inside and outside leg, the mean deviation between the measured and simulated track was 0.025 and 0.018 m, respectively (**Figure 3A**). The speed of the skier increased from about 13.5 m/s to 14.5 m/s during the simulated turning maneuver and matched the measured speed with a root mean squared difference of 0.12 m/s (**Figure 3B**). For the speed comparison, the midpoint between the right and left hip joint center was chosen as the reference point. The turn radius of the center of mass of the skier dropped at the beginning of the steering phase to a minimum of about 16 m and remained almost constant afterwards in the range from 18 to 19 m (**Figure 4A**).

3.2 Ground Reaction Forces

In the simulation of the turning maneuver, the ground reaction forces were higher on the outside leg compared to the inside leg (**Figure 4B**). Computing the force distribution between the inside and outside leg, about 60% of the total ground reaction force was acting on average on the outside leg. Consequently, the load on the outside leg was on average 50% higher. Peak forces reached 1.00 BW and 0.94 BW on the outside and inside leg, respectively. The local maximum at the beginning of the steering phase was induced by the skier performing an unloading-loading motion after the phase of edge change and the beginning of the steering phase (see animation provided online as **Supplementary Material**).

TABLE 1 | Root mean squared difference (RMSD) between the measured joint angles of the skier during the turning maneuvers and the corresponding joint angles of the musculoskeletal skier model in the tracking simulation. Minimum and maximum values of the joint angles of the skier during the turning maneuvers are reported, additionally.

	–	RMSD	Minimum	Maximum
Pelvis (deg)				
—	Tilt	0.73	-38.7	-28.3
	List	2.72	14.6	33.4
	Rotation	2.60	-18.4	30.3
Right hip (deg)				
—	Flexion	1.16	69.5	117.1
	Adduction	2.63	-12.6	11.1
	Rotation	2.30	-26.2	-9.5
Right knee (deg)				
—	Flexion	2.03	-114.0	-80.5
Right ankle (deg)				
—	dorsiflexion	2.04	17.2	21.4
Left hip (deg)				
—	Flexion	1.85	50.3	80.6
	Adduction	0.67	-27.0	-2.6
	Rotation	0.92	4.7	27.5
Left knee (deg)				
—	Flexion	0.62	-79.9	-56.1
Left ankle (deg)				
—	Dorsiflexion	1.21	18.3	26.7
Lumbar (deg)				
—	Flexion	2.16	-28.7	-22.8
	Bending	0.50	-4.6	0.4
	Rotation	1.06	-2.8	10.3

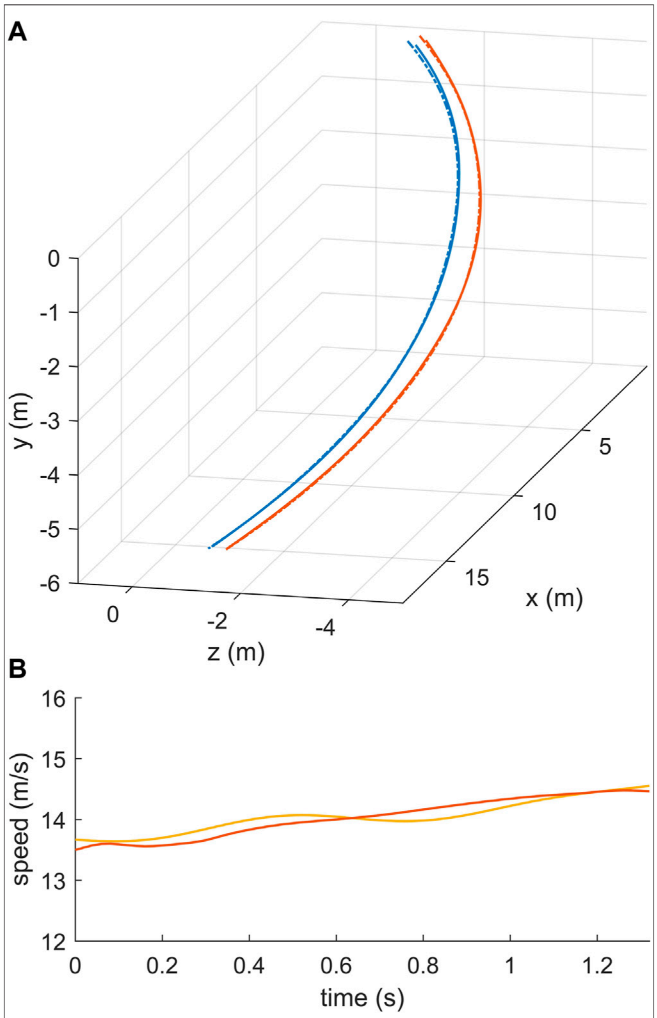

FIGURE 3 | Comparison of the optimized track of the skier in the turning simulation (solid lines) and the corresponding measurement data (dashed lines) in **(A) (B)** shows the measured (solid red) and optimized speed (solid yellow) of the skier.

3.3 Joint Moments

The highest internal joint moments were observed at the lumbar joint with a maximum value of 1.88 Nm/kg for lumbar extension. This was about 2.5 times larger compared to the maximum lumbar bending moment rising to 0.75 Nm/kg and about 12 times larger compared to maximum lumbar rotation moment (**Table 2**; **Figure 5**). At the outside leg, the highest internal joint moments corresponded to the hip extension moment with 1.27 Nm/kg, the knee extension moment with 1.02 Nm/kg and the ankle plantarflexion moment with 0.85 Nm/kg. At the inside leg, peak knee and hip extension moments were of similar order compared to the inside leg. The ankle plantarflexion moment and the passive boot moment, however, were 45 and 60% lower, respectively (**Table 2**; **Figure 5**).

The intersegmental knee joint moments in the frontal plane showed that primarily an internal adduction moment was acting on the knee joint of the outside leg during the turning maneuver (**Figure 5**), which was mainly induced by the ground reaction force passing laterally to the knee. Correspondingly, the intersegmental mediolateral force at the knee joint pointed medially to counteract the lateral component of the ground reaction force. Contrary, primarily an internal abduction moment acted on the knee joint of the inside leg during the turning maneuver (**Figure 6**) caused by the ground reaction force passing medially to the knee. Correspondingly, the intersegmental mediolateral force at the knee joint pointed laterally to counteract the medial component of the ground reaction force. Peak internal knee adduction and abduction moments reached 0.23 and 0.31 Nm/kg at the outside and inside leg, respectively (**Table 3**). In the transverse plane, the rotation moments at the knee ranged between -0.08 and 0.22 Nm/kg at the outside leg with alternating phases of internal and external rotation (**Figure 6**). At the inside leg, mainly an internal rotation moment was present throughout the turning maneuver with values ranging between 0.05 and 0.28 Nm/kg (**Table 3**).

4 DISCUSSION

The main objectives of the present study were to 1) develop a three dimensional musculoskeletal simulation model of an alpine skier and 2) apply the musculoskeletal skier model in combination with a forward dynamics optimization framework

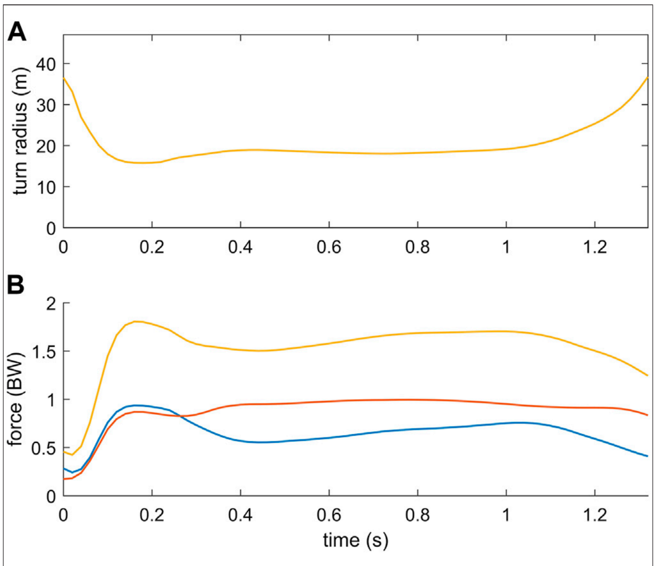

FIGURE 4 | Turn radius of the center of mass of the skier in the turning simulation **(A)** as well as the total ground reaction force, the ground reaction force acting on the outside ski (red) and inside ski (blue) **(B)**.

TABLE 2 | Peak joint moments at the lumbar joint as well as the hip, knee and ankle joint of the inside right knee and outside left knee, respectively.

Joint moments	—	Minium	Maximum
Right hip (Nm/kg)			
—	Flexion	-1.05	-0.21
	Adduction	0.00	0.45
	Rotation	-0.02	0.23
Right knee (Nm/kg)			
—	Extension	0.04	0.96
Right ankle (Nm/kg)			
—	Dorsiflexion	-0.47	0.04
	ski boot	-0.46	-0.07
Left hip (Nm/kg)			
—	Flexion	-1.27	-0.03
	Adduction	-0.39	0.52
	Rotation	-0.17	0.06
Left knee (Nm/kg)			
—	Extension	0.07	1.02
Left ankle (Nm/kg)			
—	Dorsiflexion	-0.85	0.03
	ski boot	-1.16	-0.05
Lumbar (Nm/kg)			
—	Extension	0.16	1.88
	Bending	0.01	0.75
	Rotation	-0.16	-0.01

Joint moments are represented as internal joint moments and hip flexion, adduction and internal rotation, knee extension, ankle dorsiflexion and lumbar extension, lateral bending and left rotation moments are denoted as positive.

to estimate dynamically consistent kinematics, ground reaction forces and joint moments during a turning maneuver. The estimation of the joint moments was constrained such that computed joint torques stayed within physiological limits imposed by the musculoskeletal model.

4.1 Musculoskeletal Simulation Model

We developed a novel three dimensional musculoskeletal model of an alpine skier with two skis and 53 kinematic degrees of freedom and applied it successfully to simulate and analyze a turning maneuver. To the authors' knowledge, the present study incorporates the first three dimensional musculoskeletal model for analyzing turning maneuvers in alpine skiing. In previous musculoskeletal simulation studies in alpine skiing only two dimensional models were developed (Gerritsen et al., 1996; Heinrich et al., 2014, 2018). These models were applied to analyze jump landing maneuvers in downhill skiing in the sagittal plane and possible risk factor for an injury of the anterior cruciate ligament. Developing a three dimensional musculoskeletal simulation model is computational challenging due to the increased model complexity and consequently the high computational cost involved for the optimization. To reduce the computational cost, we employed recent advances in musculoskeletal modeling and simulation. In particular, we formulated the system dynamics in implicit form (van den Bogert et al., 2011) and used direct collocation with analytical derivatives of the system dynamics to solve the underlying dynamic optimization problem (Nitschke et al., 2020).

The simulation of the turning maneuver was based on a forward dynamics optimization framework (i.e., forward assisted data tracking), where measured kinematic data of an alpine skier performing a turning maneuver were tracked by the musculoskeletal skier model. In the simulation of the turning maneuver, the experimental data of the skier could be tracked closely with a RMSD below 3° at all joints. This RMSD is considered to be low, because it is well within the precision of current mobile measurement devices such as inertial measurement units (IMU) based systems (Fasel et al., 2018b) or machine learning techniques (Ostrek et al., 2019). Additionally, the track and the speed of the skier could be tracked well. Comparing the inside and outside leg, higher errors were detected at the inside leg. The higher errors could have been caused by the higher hip and knee flexion on the inside leg during the turning. This might have complicated the manual digitization process due to occlusions and consequently reduced the accuracy of the corresponding measurement data.

In the forward dynamics optimization framework, kinematic data obtained by video-based stereophotogrammetry and a multi-camera setup were used as input data. IMU based systems in combination with a Global Navigation Satellite System (GNSS) or computer vision and human pose estimation have been shown to be promising approaches for capturing the kinematics of a skier during turning maneuvers on the ski slope (e.g., Fasel et al., 2018b; Ostrek et al., 2019). Since only measured kinematic data are mandatory in the forward dynamics optimization framework (see also next section), the present musculoskeletal simulation model might also be combined with either of these approaches in future research without the need to provide ground reaction force data captured by mobile force platforms or pressure insoles. This might open up new opportunities regarding the analysis of the loading of the skier during turning maneuvers in the natural environment if only kinematic data are available. If measured ground reaction

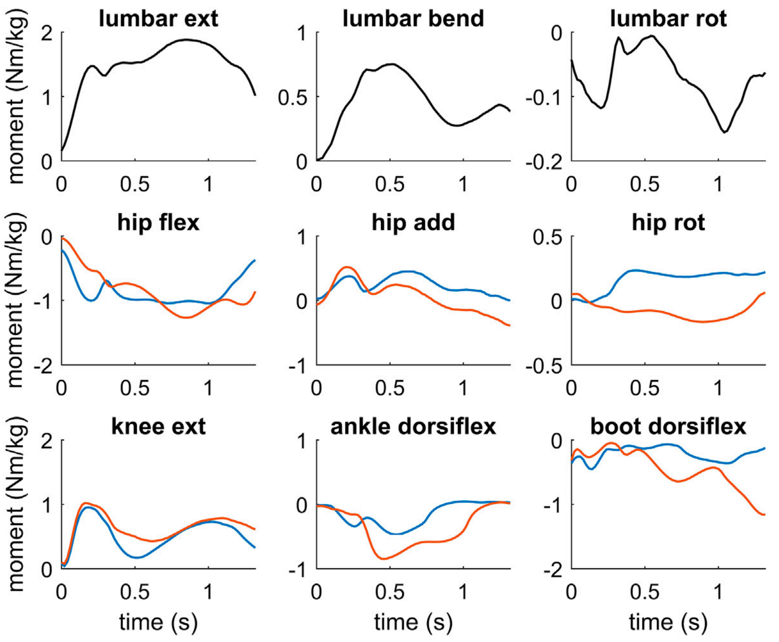

FIGURE 5 | Joint moments at the lumbar joint, hip, knee and ankle joint of the inside leg (blue) and the outside leg (red) as well as the passive joint moment induced by the ski boot at the ankle joint. Joint moments are represented as internal joint moments and hip flexion (hip flex), adduction (hip add) and internal rotation (hip rot), knee extension (knee ext) and ankle dorsiflexion (ankle dorsiflex) moments are denoted as positive. At the lumbar joint, lumbar extension (lumbar ext), lateral bending (lumbar bend) and left rotation (lumbar rot) moments are denoted as positive.

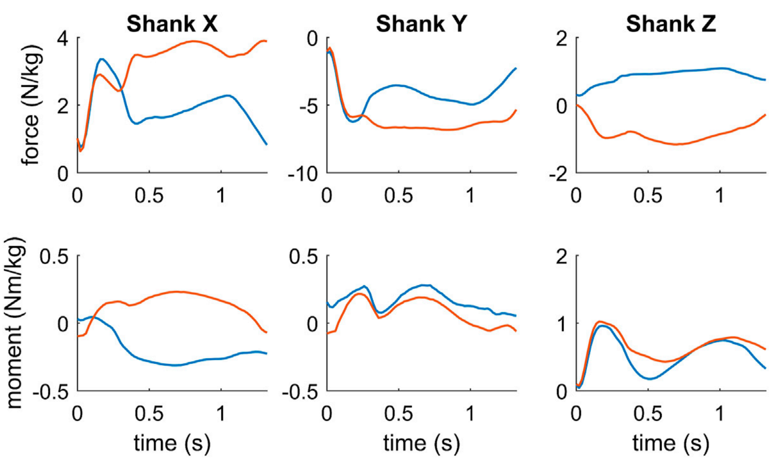

FIGURE 6 | Intersegmental forces and moments at knee joint of the inside leg (blue) and outside leg (red), respectively. Forces and moments are represented in the shank coordinate system, where the *z*-axis, *x*-axis and *y*-axis refer to the medial-lateral, anterior-posterior and superior-inferior direction. Positive joint moments denote an internal knee extension, adduction and internal rotation moment, respectively.

force, however, are additionally available as input data, these data might also be tracked in the optimization framework. Specifically, in the objective function of the optimization framework the deviation of the simulated and measured ground reaction forces might be taken into account to track the measured ground reaction forces as good as possible (van den Bogert et al., 2011; Nitschke et al., 2020).

4.2 Forward Dynamics Optimization Framework

In the present study we used a forward dynamics optimization framework to compute the joint moments during a tuning maneuver. In the literature there are only a few studies analyzing the loading of the skier during turning maneuvers dynamically (Klous et al., 2012, 2014; Hirose et al., 2013; Lee

TABLE 3 | Peak intersegmental forces and moments during the turning maneuver at the inside right knee and outside left knee, respectively, represented in the corresponding shank coordinate system.

	–	Minimum	Maximum
Right knee forces (N/kg)			
—	Fx	0.76	3.35
	Fy	-6.23	-1.07
	Fz	0.28	1.08
Right knee moments (Nm/kg)			
—	Mx	-0.31	0.04
	My	0.05	0.28
	Mz	0.04	0.96
Left knee forces (N/kg)			
—	Fx	0.63	3.90
	Fy	-6.83	-0.77
	Fz	-1.16	0.00
Left knee moments (Nm/kg)			
—	Mx	-0.10	0.23
	My	-0.08	0.22
	Mz	0.07	1.02

The z-axis, x-axis and y-axis refer to the medial-lateral, anterior-posterior and superior-inferior direction. Positive joint moments denote an internal knee extension, adduction and internal rotation moment, respectively.

et al., 2017). However, in all of these studies the authors used an inverse dynamics approach to compute the joint moments at the lower extremities. Compared to the classical inverse dynamics analysis, the present framework has four major advantages.

First, using a forward dynamics optimization framework the obtained kinematics of the skier as well as the corresponding ground reaction forces are dynamically consistent. Consequently, no residual forces and torque have to be added such that the equations of motion of the skier are satisfied (Bailly et al., 2021). This is important since residual forces and moments do not exist in reality and affect the computation of kinetic variables such as joint moments, power and work (Hatze, 2002; Faber et al., 2018). Contrary, using an inverse dynamics approach the validity of the computed joint moments is impaired depending on the size of the introduced residual forces and moments (Faber et al., 2018).

Second, optimization of a forward dynamic model with data tracking and effort minimization also has the advantage that the data being tracked can be any number of variables. The number of measurements can be overdetermined (more measurements than kinematic degrees of freedom and external loads), or underdetermined (fewer measurements than kinematic degrees of freedom and external loads). This makes it possible to perform a full dynamic analysis without external loads (i.e., ground reaction forces) provided for example by instrumented skis, as demonstrated previously in a planar analysis of jump landing in skiing (van den Bogert et al., 2011) or in the present three dimensional analysis of a turning maneuver in skiing. In contrast, classical inverse dynamic analysis requires the measurement of all kinematic degrees of freedom and external loads, not more and not less.

Third, the computed joint moments are less sensitive to errors in the measurement data, since only the measured kinematic data (i.e., joint angles, pelvic translation and orientation) are tracked in the simulation. First or second derivatives of the measured kinematic data are not required. Contrary, inverse dynamics requires the second derivative of the measured kinematic data, which amplifies measurement errors (Cahouët et al., 2002; Pàmies-Vilà et al., 2012).

Fourth, the computed joint moments are constrained to stay within physiological limits. The physiological limits were induced by the musculoskeletal model, which included a three element Hill-type muscle model with activation and contraction dynamics. Contraction dynamics incorporates the force-length-velocity characteristics of the muscle, the active state as well as the maximum isometric force (van den Bogert et al., 2011) and limits the acting muscle forces and the corresponding joint moments. In addition, the activation dynamics limits the change of the corresponding joint moments, incorporating time constants for muscle activation and deactivation in the dynamics equation (Bailly et al., 2021).

4.3 Joint Moments

Based on the musculoskeletal model and the forward dynamics optimization framework we computed the joint moments at the lumbar joint as well as the hip, knee and ankle joints of the outside and inside leg of the skier during the turning maneuver. At the outside leg, highest lower-limb joint moments were identified at the hip joint (1.27 Nm/kg, hip extension), followed by the knee joint (1.02 Nm/kg, knee extension) and ankle joint (0.85 Nm/kg, ankle plantarflexion). Knee and hip extension moments were similar at the outside and inside leg, although the ground reaction forces were on average about 50% higher on the outside leg. This can be explained by the increased knee and hip flexion on the inside leg, which required higher activation of the knee and hip extensor muscles. The ankle plantarflexion moment and also the passive boot moment were lower on the inside leg, which indicated that the skier was pushing more against the shaft of the ski boot at the outside leg.

In accordance with the present study, the hip extension moment was reported as the highest joint moment in the kinetic studies of Hirose et al. (2013) and Lee et al. (2017) analyzing turning maneuvers in skiing based. In both studies, the authors used on an inverse dynamics approach to compute the joint moments given kinematic data from an IMU based system and measured ground reaction forces. Specifically, in the study of Lee et al. (2017), the peak knee extension moment (0.5 Nm/kg) and ankle plantarflexion moment (1.1 Nm/kg) were roughly of the same order of magnitude as in the present study. Strikingly, however, the peak hip extension moment reached 6 Nm/kg. In the study of Hirose et al. (2013), the hip extension moment reached 12 Nm/kg assuming a mass of the skier of 75 kg. Compared to the present study, these reported peak hip extension moments are a factor of 5 and 10, respectively, higher and are likely to be unrealistic high. In particular, these values exceed reported maximum voluntary joint moments by about 70 and 240%, respectively, if we take the data of the age group 19–25 in the study of Anderson et al. (2007) as reference data and add one standard deviation to the mean value. Unfortunately, Hirose et al. (2013) and Lee et al. (2017) did not present any information about the external forces acting on the skier (i.e., ground reaction forces or speed and turn radius of the skier) or the kinematics of the skier, which makes a more detailed comparison impossible. On the other hand, similar hip extension moments as in the present study were reported in the study of van den Bogert et al. (1999). Nine male subjects were instrumented with a 12-channel accelerometer system mounted on the upper body and the hip extension moment was computed through an inverse dynamics analysis. The authors reported an average peak hip extension moment of 1.75 Nm/kg during long turns on a flat slope assuming a mean mass of the skiers of 75 kg. The skiers were asked to load the outer ski only and lift the inner ski, which shifted the entire load to the outer ski. In contrast, only 60% of the external load was acting on the outside leg of the skier during the turning maneuver in the present study.

The internal knee joint moments showed that in the frontal plane primarily an adduction moment was acting on the knee joint of the outside leg in combination with alternating phases of an internal and external rotation moment in the transverse plane as well as a knee extension moment. Klous et al. (2012) studied the loading of the knee joint during a carved and skidded turn. The turn radius of the skier was about 10 m in both turns, while the mean speed during the carving turn was higher than during the skidded turn (13.9 m/s vs 10.4 m/s). The authors determined peak knee extension moments up to 8.35 and 4.07 Nm/kg for the skidded and carved turn, respectively, based on an inverse dynamics approach. In addition, they computed peak adduction moments up to 5.70 and 5.75 Nm/kg in the frontal plane and external rotation moments up to 6.85 and 2.75 Nm/kg in the transverse plane for the skidded and carved turn. All of these values are significantly higher compared to the values of the present study. The differences might be explained in part by the decreased turn radius of the skier in the study of Klous et al. (2012), which induced a higher external loading onto the skier. However, due to measurement noise and the limitations of the inverse dynamics approach, the computed joint moments might have been overestimated exceeding physiologically plausible values. For example, if we compare the peak knee extension moments with literature data such as maximum voluntary knee extension moments (Anderson et al., 2007) or maximum isometric knee extension moments (Pincivero et al., 2004; Domire et al., 2011), these values are unrealistic high. In addition, the reported knee abduction moments are about three times higher than the assumed injury threshold of 125 Nm valgus moment (= 1.67 Nm/kg assuming a mass of 75 kg) in the study of McLean et al. (2008), although they did not investigate an injury prone situation.

Interestingly, in the present study the peak joint moment at the lumbar joint exceeded the peak values at the lower limbs during the turning maneuver. In particular, the lumbar extension moment rose up to 1.88 Nm/kg, while the lateral bending and rotation moments were remarkably lower. Consistent with the results of the present study, the highest joint moment was observed at the lumbar joint for lumbar extension in the study of Hirose et al. (2013). High values at the lumbar joint imply that the lower back of the skier is subjected to high loads during turning maneuvers. These high values may be linked to lower back pain, which is a common overuse injury in alpine skiing (Spörri et al., 2018). Furthermore, it has been reported that the combination of lumbar flexion, lateral bending and axial rotation amplifies the loading at the lower back (Spörri et al., 2018). Further studies, however, and a more sophisticated model of the lower back are necessary to quantify the internal loading at the lower back in more detail.

4.4 Limitations

Some limitations of the present study have to be mentioned. First, in the simulation of the turning maneuver we did not track the movement of the arms of the skier. The reason was to reduce the complexity of the model and to decrease computational time, which is one of the big challenges in three dimensional musculoskeletal simulations. However, since we included the mass and inertia properties of the arm in the model and assumed a mean posture of the arms in front of the skier, the impact on the computed joint moments is expected to be low.

Second, we did not implement a detailed spine model, but used a single lumbar joint at the lower back. Consequently, the present simulation model is expected to provide only basic features regarding the loading of the lower back of the skier turning maneuvers. While these basic features might contribute to the understanding of lower back pain, which is a common overuse injury in alpine skiing (Spörri et al., 2018), a more detailed spine model might provide further insight.

Third, in the present simulation study we analyzed data of a professional skiing instructor performing a giant slalom turning maneuver. Changing the characteristics of equipment, the present simulation model might also be used to analyze turning maneuvers in other disciplines such as slalom, super-G (super giant slalom), or downhill skiing. Furthermore, the present simulation model might also be used to analyze jump landing maneuvers in super-G and downhill, which have been identified as a common situation leading to injury (Gilgien et al., 2014). Regarding jump landing maneuvers the present simulation model might extend the current knowledge derived from two dimensional simulation models (Heinrich et al., 2014) regarding the loading of the skier in the frontal and transverse plane.

5 CONCLUSION AND OUTLOOK

In the present study we developed a novel three dimensional musculoskeletal simulation model to analyze the kinematics and kinetics (i.e., the intersegmental moments at the knee joint) of a skier during turning maneuvers. While the focus of the present study was on the joint moments acting on the skier, the present musculoskeletal model might also be applied to analyze muscle forces and further characteristics related to muscle function such as muscle length change, muscle contraction velocity, muscle power and muscle work (van den Bogert et al., 2013). Kinematic data captured by a multi-camera setup were used as input data. In future applications, the present simulation model might also be used in combination with kinematic data obtained by mobile measurement devices (i.e., IMU and GNSS based systems) or machine learning techniques (i.e., human pose estimation) providing additional insight into the loading of the skier during turning maneuvers.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

DH and WN designed and planned the study. AV and DH developed the musculoskeletal model. All authors contributed to data analysis and interpretation. DH wrote the initial draft of the manuscript. WN and AV revised the manuscript critically. All authors approved the final version of the manuscript.

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SUPPLEMENTARY MATERIAL

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Peter A. Federolf,
University of Innsbruck, Austria

REVIEWED BY
Wolfgang Immanuel Schöllhorn,
Johannes Gutenberg University Mainz,
Germany
Carson Patterson,
University of Innsbruck, Austria

*CORRESPONDENCE
Christian Magelssen,
cmagelssen@gmail.com

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Is there a contextual interference effect for sub-elite alpine ski racers learning complex skills?

Christian Magelssen[1]*, Per Haugen[1], Robert Reid[2] and Matthias Gilgien[1,2,3]

[1]Institute for Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway, [2]The Norwegian Ski Federation, Oslo, Norway, [3]Center of Alpine Sports Biomechanics, Engadin Health and Innovation Foundation, Samedan, Switzerland

Scientific understanding of the contextual interference effect stems mainly from studies on unskilled participants learning artificial laboratory tasks. Although one goal of such studies is to extrapolate the findings to include real-world learning situations such as sports, this generalization is not straightforward. This study tested the contextual interference effect with 66 sub-elite, competitive alpine ski racers who learned a new movement pattern–the pumping technique to increase velocity in slalom–by practicing this skill in three different slalom courses over a 3-day training period. The interleaved group practiced all three courses each day in a semi-random order. In contrast, the blocked group practiced only one course each day, which was randomized and counterbalanced across the participants in this group. A retention test was delivered 72 h after the last practice day. In contrast to our hypothesis, the interleaved group did not display significantly better retention than the blocked group. The interleaved group's performance was also not significantly attenuated during skill learning compared to the blocked group. Our results underscore the importance of conducting motor learning experiments in natural environments to understand the conditions that facilitate learning beyond the laboratory environment.

KEYWORDS
contextual interference, motor learning, alpine ski racing, sport expertise, retention, pumping to increase velocity, course setting

1 Introduction

Many studies suggest that training with a high degree of contextual interference can create favorable conditions for learning motor skills (Magill and Hall, 1990; Lee and Simon, 2004; Merbah and Meulemans, 2011). Experiments on the contextual interference effect usually introduce learners to three tasks to be learned (tasks A, B, and C). In the high contextual interference condition (i.e., interleaved practice), the practice order of tasks makes the learner frequently switch between the tasks they acquire (for example, ABC, BAC, or CBA). In contrast, less switching occurs in the low contextual interference condition (i.e., blocked practice) by arranging the tasks in blocks (for example, AAA, CCC, BBB). Previous research has provided evidence that interleaved practice often improves skill preservation over time (i.e., retention) and adaptation of the skill to new situations (i.e., transfer) compared to blocked practice. However, a notable aspect is that blocked practice often results in superior performance during skill acquisition compared to the interleaved group. This paradoxical interaction—called the contextual interference effect—represents a prime example of the distinction between performance and learning in motor learning and has been extensively replicated in a wide variety of scientific laboratory experiments (Shea and Morgan, 1979; Lee and Magill, 1983; Simon and Bjork, 2001; Thomas et al., 2021).

Despite the existence of ample evidence for the contextual interference effect being present in laboratory environments, it has become clear that the principles deriving from the research do not always generalize to the learning of motor skills in naturalistic settings such as sports (Wulf and Shea, 2002; Brady, 2004; Barreiros et al., 2007). For example, Barreiros et al. (2007) have reported that the proportion of studies showing improved retention due to interleaved practice was considerably smaller for skills performed in a natural environment than for skills performed in a laboratory environment. Furthermore, a meta-analysis showed that the contextual interference effect is typically smaller and more dispersed than in laboratory tasks (Brady, 2004). Therefore, while interleaved practices may improve learning for simple tasks, the evidence for contextual interference for learning more complex tasks in natural environments is not conclusive.

Over the years, researchers have proposed and examined several different moderators to account for the contradictory results between laboratory and natural environments, including the learner's age (Del Rey et al., 1983), the amount of practice (Shea et al., 1990), the type of task (Magill and Hall, 1990), the modality-specific requirements of the task (Schöllhorn et al., 2022), and the learner's skill level relative to the difficulty of the task (Wulf and Shea, 2002; Guadagnoli and Lee, 2004). Concerning the latter of these moderators, the challenge-point framework (Guadagnoli and Lee, 2004) posits that the efficacy of interleaved practice depends on the difficulty of the task as it is objectively defined (that is, nominal task difficulty) but also how challenging the task is relative to the learner's skill level and practice environment (that is, functional task difficulty). The framework predicts that an interleaved practice may be more beneficial to promoting learning in a context involving learning a task with low nominal difficulty (for example, a simple laboratory task). This expected observation is because interleaved practice increases the functional difficulty of the task to engage the cognitive mechanisms responsible for causing the contextual effect. With more nominally difficult tasks, the task's characteristic may already be sufficiently challenging to achieve this end so that beginners may benefit from the blocked practice. However, as learners become better at the task, increasing the functional difficulty of the task through interleaved practice may be needed to engage the cognitive mechanisms to promote additive learning. In support of the challenge-point framework, several studies have provided evidence that providing beginners with a gradual and systematic increase in contextual interference when learning complex skills seem to be a better learning approach than the sole use of blocked or interleaved practice (Porter and Magill, 2010; Saemi et al., 2012). These findings suggest that the optimal practice condition changes with the learner's proficiency and the skill's complexity.

The challenge point framework and the supporting evidence that the learner's skill level interacts with the characteristic of the task in determining the contextual interference effect can build the impression that skilled performers benefit from training with a high degree of contextual interference when improving or refining their skills. Even though some researchers have advocated such an approach (Christina and Bjork, 1991; Schmidt, 1991), few studies have explicitly tested it. One of the few exceptions is a study on skilled baseball players who performed additional batting training to probe the contextual interference effect (Hall et al., 1994). Three groups practiced batting with three types of baseball pitches. The blocked group practiced these pitches in a blocked order (AAA, BBB, CCC), whereas the interleaved group practiced them in a random order (BCA, ABC, BAC). At the end of the training intervention, the interleaved group performed better than the blocked group. This study demonstrated that interleaved practice might also improve learning for skilled performers. It is important to note that Hall et al. (1994) used variations of a single skill (i.e., batting) to probe the contextual interference effect. In a recent study, Buszard et al. (2017) performed a between-skill manipulation to examine the contextual interference effect in youth tennis players. While interleaving the practice schedule did not improve retention for these players compared to the blocked practice schedule on the same task, there was evidence that the interleaved group transferred their skill better to competition (i.e., transfer). Hence, it remains unclear whether training with contextual interference improves learning for skilled performers when improving their skills. This lack of understanding is critical to address in order to provide proper recommendations for instructors in sports and other motor activities, such as surgical operations in medicine and the training of military personnel.

Testing the contextual interference effect on skilled performers implies specific challenges that must be overcome and effectively solved. The biggest challenge is that skilled performers are usually obsessed with achieving success in their activity and devote significant amounts of their time and resources to improving their performance in this activity. Therefore, recruiting them for a study is often challenging because of their reluctance to modify their training for an experiment, especially if it does not lead to immediate performance gains (Farrow and Buszard, 2017). Even if performers were willing to participate, it would often require a large volume of practice to improve the performance of a skilled practitioner compared to a novice performer (Hall et al., 1994). Hence, even if interleaved practice makes the training more effective, the effect may only become visible after extensive practice, regardless of the skills training method. A final obstacle is that it is often difficult to achieve a robust and sensitive performance goal, especially in alpine ski racing, where external conditions such as snow and wind vary considerably and may influence performance (Williams et al., 2017). Overcoming these challenges requires in-depth knowledge of the skill domain, and real-world practitioner skills are needed to invent innovative approaches to assess skills and deal with issues of validity at the same time (Farrow and Buszard, 2017).

Considering the need for a better understanding of how the contextual interference effect translates to skilled learners, and how to cope with the described challenges, we have investigated the contextual interference effect on skilled athletes in the complex sport of alpine ski racing in this study. Alpine ski racing is a sport where performance is measured as the time from start to finish, where athletes need to pass through a pre-defined course marked with gates. The sport consists of six main disciplines: slalom (SL), giant-slalom (GS), super-G (SG), downhill (DH), Parallel and Combined, which vary in the number of direction changes,timing and dynamics in turns,terrain and transitions, course length, and jumps (Gilgien et al., 2018). Of these six disciplines, slalom skiing is the most technically demanding due to its frequent changes of direction, high turn forces, and small turn radii (Reid, 2010). Slalom courses generally comprise ~50 gates, adjacently positioned with a linear distance of 6–13 m. These courses can vary extensively between races depending on the course setter, usually a coach who can determine the type of course within the rules of Fédération International de Ski (FIS). Besides the variability in courses, there is also large variability in terrain characteristics (for example, incline and terrain transitions), snow properties, and weather (for example, visibility). Slalom racers should therefore expect a significant degree of variability in conditions in the performance arena.

Although the total time differences between skiers in slalom races can be quite small, section differences through a course can be quite significant while typically equalizing to small differences at the finish (Supej and Cernigoj, 2006; Supej and Holmberg, 2011). The sections of slalom courses where significant time differences typically occur between skiers are flat terrain sections (Supej and Cernigoj, 2006). An essential characteristic of flat sections is that the component of gravity that accelerates the skiers downhill is small (Reid, 2010). Therefore, the skier must make the necessary adjustments to their technique to ski fast in this type of terrain (Supej et al., 2015). One technique proposed to help increase speed in flat terrain is to “pump” while turning to increase the turn exit speed (Mote and Louie, 1983; Lind and Sanders, 2004). In this context, pumping refers to the technique of extending the legs and pushing the center of mass towards the axis of rotation at the center of the turn. Through the conservation of angular momentum, pushing the center of mass closer to the axis of rotation can lead to increased tangential velocity (Lind and Sanders, 2004). Therefore, the extent and quality with which skiers can exploit this technique can be a primary explanation for the time differences in flat sections.

Because the technique that leads to good performance differs depending on the terrain incline, researchers have recommended dividing training into sessions with uniform terrain inclines to achieve more element-focused training (Supej et al., 2015). Once training in a section of uniform terrain incline, coaches need to determine the slalom gates’ location down the hill. The location of the gates determines two characteristics of the course: the linear distance between successive gates determines the room skiers have for turning between gates, and the offset determines how “turny” the course is. Changes in these two course dimensions can cause significant changes in the required technique, and the tactics skiers must use to ski the course. For example, changes in gate offset have been shown to reduce speed and turn radius but increase turn forces, impulse (a measure of physical load), and inward lean for giant slalom and super-G (Spörri et al., 2012; Gilgien et al., 2020, Gilgien et al., 2021). In contrast, shortening the linear distance between gates causes a reduction in turn time and speed but has a limited effect on forces and turn radii compared to changes in the offset (Reid, 2010; Gilgien et al., 2020, 2021). Because course setting has a significant impact on skiers’ technique and is the training variable that coaches can influence the most, there is a general conception that this is one of the most critical variables affecting learning.

Because skiers never know what courses and conditions to expect in a race, they must master an extensive range of conditions. Therefore, undertaking training to perfect performance in a single course setting may not be effective. Instead, researchers have argued that a better approach is to use interleaved practice in these types of open sports (Farrow and Buszard, 2017). However, few studies have tested this recommendation due to the described challenges of conducting studies on complex learning tasks with skilled performers. Therefore, we established this study to test the contextual interference effect with skilled alpine ski racers in a realistic real-world ski racing environment. An important goal was to do the study with a large number of participants to estimate the contextual interference effect robustly. To achieve this goal, we designed a study that targeted a particular skill element of skiing performance that was relevant for the skiers to improve. Targeting this specific element instead of providing holistic training, we were also able to improve the skiers’ performance by a significant degree, because training this skill was novel for the participants.

In this study, we expected contextual interference to apply to the training of alpine ski racers. Our rationale for expecting an extension of the effect to this context emerged from previous studies that reported improved retention of continuous skills (cyclic bimanual coordination task) resulting from interleaved compared to blocked practice (Tsutsui et al., 1998; Pauwels et al., 2014). Moreover, in a snow environment, Smith (2002) reported that novices learned snowboarding turns better after practicing four different turns (left/right and heel/toe) in an interleaved compared to a blocked order. This finding suggests that contextual interference may be relevant for learning skills in alpine ski racing. If skiers vary their turns in an interleaved manner, as is accomplished by frequently switching between courses, we could expect to observe contextual interference in alpine skiing. In the snowboarding study, however, the participants were novices, and it is unclear how this extrapolates to skilled performers. Based on the previous research that has provided evidence for the contextual interference for experienced performers (Hall et al., 1994), we hypothesized that interleaved practice would suppress performance during acquisition but improve performance at retention.

2 Material and methods

2.1 Participants

Sixty-six competitive alpine ski racers (31 females), aged between 14 and 28 (*Mean age* = 17, *SD* = 2.7 years), were recruited from three different ski clubs and four high school-level development academies affiliated with the Norwegian Ski Federation (NSF). Except for a smaller subset of the participants (n = 12) who competed in national races for skiers between 14 and 16 years, the participants had participated in Fédération International de Ski (FIS) races and had recorded FIS points. Our sampling approach was to recruit as many skiers as we had access to in eastern Norway. By the end of the experiment, we had recruited participants from almost every ski academy in the region. Unfortunately, 12 of these 66 participants either ended up in Covid-19 quarantine after the last practice session, or were sick, reducing the sample to 54 participants who completed the entire protocol. Given this final sample size, the study had 11% and 44% power to detect a small and medium-sized effect, respectively, in comparing groups in the main outcome (see Supplementary Material for specific details of the power calculations).

All participants provided written informed consent prior to the study. Where participants were less than 15 years of age, we also required informed consent from their parents/guardians. The protocol was approved by the Human Research Ethics Committee of The Norwegian School of Sport Sciences.

2.2 Task and apparatus

Our intervention targeted the improvement of the pumping technique in the discipline of slalom skiing. To create a learning situation where the pumping skill could be trained and assessed under controlled and stable conditions, we used a 250-meter-long, relatively flat section of the race hill in the indoor skiing hall in Oslo, Norway (https://snooslo.no/). Having stable external conditions was especially important in this study because the intervention spanned multiple days, and changes in external conditions could influence the results. Therefore, we performed the study indoors, obtaining stable wind and light conditions. Only minor changes in temperature and snow conditions needed consideration, which we dealt with by water-injecting the snow before each round of data collection to provide race-like snow surface conditions. In addition, the snow surface was maintained manually before and during each day of training and testing. We recorded the temperatures in the snow hall, and we asked participants individually to rate the snow conditions after each ski day.

To create tasks that required different ways of pumping (that is, different timing and amplitude), we set three slalom courses (A, B, and C) that had different gate offsets: for courses A, B, and C, we used 1.2-, 1.7- and 2.2-meter gate offsets, respectively (Figures 1A, B). However, all courses had a vertical gate distance of 10 m due to space constraints in the skiing hall that forced us to set the courses parallel. We deliberately chose the specific gate offsets from several pilot tests with skiers that fitted the participants' skill levels in the study. The courses were within the range that let participants pump yet were perceived as very different types of courses. Performance time was measured with photocells set up 10 m after the start and at the finish. The time started when the participant crossed the first photocell and stopped when the participant crossed the last photocell (Figure 1A). We used a wireless photocell timing system (HC Timing wiNode and wiTimer, Oslo, Norway) to measure these times.

Participants performed all runs from the same starting line and with a standardized starting procedure to avoid confounding the task with different entrance speeds into the course. Participants had to start in a stationary position and ski straight out of the starting gate to the first photocell with no poling or skating to generate propulsion.

Besides using the ski hall to limit the impact of external conditions on performance, we included three straight gliding runs each day to capture the effect of any potential change in snow conditions on performance. The straight gliding lane was set between courses A and B, where the participants skied the

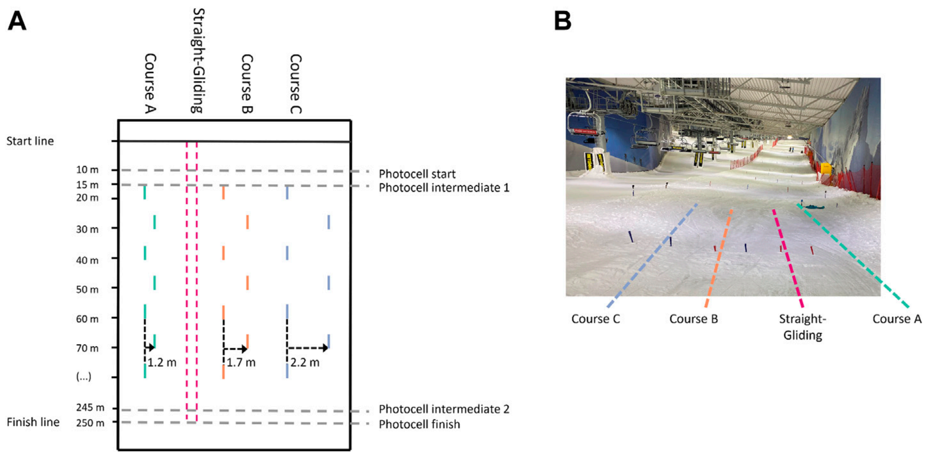

FIGURE 1
The experimental set-up of this study. **(A)** This figure depicts the three slalom courses with the different offsets. In the straight-gliding line between course A and course B, participants skied the section straight down in a static, upright position. Timing started when the participant crossed "photocell start" and ended when the participant crossed "photocell finish". **(B)** The same courses seen from the starting area.

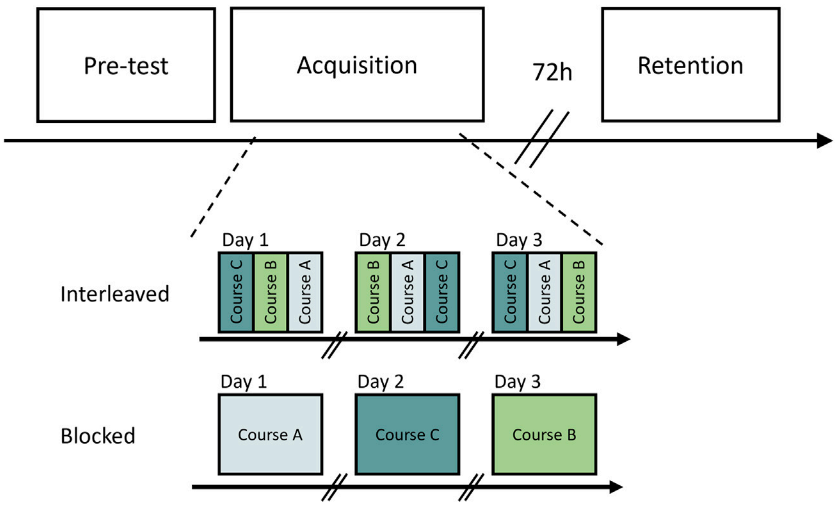

FIGURE 2
The design of this study. On day 1, all participants performed a pre-test that consisted of three runs in each of the three slalom courses, performed in an interleaved order. Based on their performance on this test, the participants were stratified into two approximately equal groups. Participants in the interleaved group skied all courses each day, executed in an interleaved order under the condition that no more than two runs in the same course would occur consecutively. Participants in the blocked group performed all runs on a single course (i.e., course A, B or C) in a given practice session. The order in which the participants performed the course was counterbalanced across participants. After a retention interval of 72 h, the participants returned to complete a retention test that was similar to the pre-test.

250-meter section in a straight line from start to finish. The straight gliding was completed in an upright, stationary posture to create a similar drag area for each run. This procedure allowed us to evaluate changes in ski snow friction that were not influenced by changes in air drag (due to changes in the frontal area). Including the straight gliding runs enabled us to normalize the performance time results between different test days.

2.3 Procedure

The participants completed the experiment in groups of 10–20. Depending on the size of the ski club and academy, groups consisted of participants from a single ski club or academy or were composed of a larger group from several ski clubs and academies. Participants could continue their regular dryland training, but no ski-related training was allowed during the intervention and test period. See Figure 2 for an overview of the study design.

2.3.1 Pre-test

After completing a demographic questionnaire about their age and gender, participants inspected the three slalom courses. First, they completed two warm-up runs: one free skiing and one in a randomly selected course. Then, participants were instructed to complete 12 runs on each of the slalom courses (course A, B, and C) and three straight-gliding runs in the straight-gliding lane. The participants performed the slalom courses in a semi-random order except for the first and last runs, which were straight-gliding runs. In accord with previous studies, the semi-randomization ensured that no more than two consecutive runs were conducted on the same course. Testing participants in a random rather than a blocked order was done because this procedure has yielded the most notable differences between blocked and interleaved groups. This testing also simulates the competitive environment of alpine skiing, where courses constantly change from one race to another. The participants were instructed to ski the courses as fast as possible, but they did not receive any feedback on their performance from the timing system this day.

After the pre-test, participants attended a workshop where we introduced the concept of "pumping to increase velocity" and the physical principles underlying the effect. The workshop lasted for 30 min and included video materials and empirical evidence from alpine skiing to give a conceptual understanding of the skill. At the end of the workshop, we informed the participants that the goal of the training intervention was to explore pumping motion strategies to maximize the effect of pumping to increase velocity during the three practice sessions. Furthermore, we told them that they did not have a coach for these sessions but should use the feedback system that provided objective feedback to evaluate their performance.

2.3.2 Acquisition

After the pre-test, the participants were quasi-randomly assigned to interleaved or blocked groups based on their pre-test scores. Specifically, for each participant, the best run of the pre-test in each of the three courses was extracted and divided by the average of the straight gliding runs from the pre-test. The participants were then ranked from fastest to slowest and paired in ascending order. Finally, each consecutive pair from this list were shuffled into an interleaved or blocked group.

Participants executed 15 runs each training day: 12 runs on the three courses and three straight-gliding runs in the straight-gliding lane. For the 12 runs executed in the courses, participants in the interleaved group skied all courses each day. The execution of these was randomized in an interleaved order, ensuring that no more than two runs on the same course would occur consecutively. Participants in the blocked group performed all runs on one course (course A, B, or C) on a given day of practice. The order in which the course was performed was counterbalanced across participants.

After each run, all participants received performance feedback from a display at the finish that showed the difference between the actual run and their straight-gliding time (in seconds). Participants were instructed to use the difference between the straight gliding time and the actual run time to evaluate their current performance and try to reach or beat this straight gliding time when skiing in courses A, B, and C using the pumping motion to increase their speed.

2.3.3 Retention

Seventy-two hours after the last practice session, participants returned to complete the retention test, consisting of 12 runs [three runs in each of the three slalom courses (A, B, and C) and three straight-gliding runs]. As in the pre-test, every participant started and ended the testing session with a straight-gliding run. Except for these two straight-gliding runs, the remaining runs were scheduled in a semi-random order to avoid more than two runs being skied consecutively in the same course. Participants were again instructed to ski as fast as possible but did not receive any feedback on their performance during the post-test.

2.4 Data processing

2.4.1 Snow condition

To assess the snow conditions, a modified version of the online questionnaire on perceived piste properties, as proposed by Wolfsperger et al. (2015) was employed. Specifically, the participants were asked to judge three characteristics of the snow conditions on the courses each day. The "homogeneity of the course" was assessed on a scale ranging from −3 to 3, where three indicated complete homogeneity of the snow conditions across and within courses, whereas −3 indicated very different conditions. The "mechanical resistance of the snow" was rated on a scale ranging from (−3 to +3), where −3 indicated hardness and +3 indicated softness. Finally, the participants indicated the "grippiness of the snow" on a scale ranging from −3 to +3, where −3 corresponded to grippy and +3 indicated slick/icy. The participants rated these characteristics in the upper and lower part of the course separately. Means and standard deviations of the participants' responses across courses and upper/lower parts were calculated to describe the snow conditions for each day.

2.4.2 Acquisition

Each run in the slalom courses (A, B, and C) was subtracted from the average straight-gliding time a participant had achieved on the respective training day. The rationale for performing this normalization was to describe how much faster or slower a skier was than his/her straight gliding on the respective day. Also, the normalizing of the data allowed us to compare participants' performance across days despite minor changes in course length or snow conditions. Runs where a participant for some reason did not finish the course (e.g., due to a mistake or straddling a gate) were omitted. Next, the runs were numbered from 1 to 12 and arranged in ascending order. The runs were subsequently batched into three Acquisitions Trial Blocks (1–4, 5–8, and 9–12 were batched into Acquisition Trial Blocks 1,2 and 3, respectively) for each of the three courses, following the convention adopted from previous studies on contextual interference (Shea and Morgan, 1979; Lee and Magill, 1983). Finally, we calculated the average performance within each batch. Acquisition performance was also calculated and included in the results for participants who dropped out from the retention test.

2.4.3 Retention

Retention was calculated as the average time of the runs in each of the three courses, subtracted from the average straight-gliding time a participant recorded that day. Runs where a participant did not finish the course (e.g., due to a mistake, or straddling a gate) were excluded. This calculation was used to normalize the performance across different days and groups to assess a participant's performance even if the course length or condition was slightly different.

2.5 Statistical analysis

Because participants took part in the experiments as groups of 10–20 from ski clubs and academies during different weeks, external conditions such as snow and the social environment were subject to change. Therefore, we used linear mixed-effect regression models to account for this variation in our models. In addition, linear mixed regression models allowed us to include available information from participants with missing data points in any of the three courses.

To analyze the data, we used linear mixed-effect regression models. To analyze whether the blocked practice group outperformed the interleaved practice group during acquisition, we used a linear mixed-effect regression model to predict performance with Acquisition trial block (1, 2, 3) and Course (A, B, C) as within-subjects factors and group (interleaved, blocked) as the between-subjects factor. To analyze whether the interleaved practice group outperformed the blocked practice group on retention, we predicted retention performance with the main effect and interaction of group (interleaved, blocked) as a between-subjects factor, Course (A, B, C) as the within-subjects factor, and pre-test performance as a covariate. We included a random intercept for both Bib and Academy in both models to account for dependency structure in the data. The models were fitted using the lme4 (Bates et al., 2015) package in R (R Core Team, 2021). *p*-values were obtained from the lmerTest package (Kuznetsova et al., 2017) using the Satterthwaite degrees of freedom method, which yields the most acceptable Type-1 error rate for small sample sizes (Luke, 2017). ANOVA outputs from both these models were reported to ease interpretation and to be consistent with previous literature on the contextual interference-effect. To this end, estimated marginal means were derived from the emmeans package (Lenth, 2021) and the Satterthwaite degrees of freedom. Due to the lack of consensus on calculating standardized effect sizes for linear mixed-effect regression models, we followed the recommendation to report raw effect sizes with a 95% confidence interval (Lohse et al., 2020). We performed visual inspections of the residual plots to assess the uniformity of variance.

We registered the analysis plan after the first round of data collection (https://osf.io/xqte2/). *p*-values < 0.05 were considered statistically significant for the entire study.

3 Results

3.1 Descriptive data

Descriptive statistics for the participants' evaluation of the snow conditions each day are presented in Table 1.

3.2 Acquisition

Figure 3 shows the acquisition data for the interleaved and blocked groups. The linear mixed-effect regression model revealed a main effect of Time, [F (2, 500.21) = 48.89, $p < 0.001$]. Participants improved their performance from the first [M = 0.70; 95% CI (0.18, 1.23)] to the second [M = 0.49; 95% CI (−0.03, 1.02)] and third [M = 0.37; 95% CI (−0.16, 0.89)] acquisition trial blocks. The model also revealed a main effect of Course, [F (2, 501.94) = 1792.84, $p < 0.001$]. Participants tended to ski course A [M = −0.45; 95% CI (−0.98, 0.08)] in a shorter time than course B [M = 0.42; 95% CI (−0.11, 0.94)] and course C [M = 1.59; 95% CI (1.07, 2.12)]. However, no main effect of Group was observed, [F (1, 61.90) = 0.49, $p = 0.488$]. Averaged across Acquisition trial block and Course, the performance of the blocked group [M = 0.50; 95% CI (−0.13, 1.13)] was only 0.11 s slower than the interleaved group [M = 0.53; 95% CI (−0.10, 1.16)]. No higher-order interactions involving the Group variable were found: Acquisition trial block x Group, [F (2, 500.2) = 2.11, $p = 0.122$]; Acquisition trial block x Group x Course, [F (4, 499.46) = 0.76, $p = 0.553$].

3.3 Retention

Figure 3 shows the acquisition data for the interleaved and blocked groups. The linear mixed-effect regression

TABLE 1 The table shows the average rating of the three snow characteristics and the standard deviation in parenthesis for each day. The "*homogeneity of the course*" was assessed on a scale ranging from −3 to 3, where three indicated complete homogeneity of the snow conditions across and within courses whereas -3 indicated very inhomogeneous conditions. The "*mechanical resistance of the snow*" was rated on a scale ranging from (−3 to +3), where −3 indicated hardness and +3 indicated softness. Finally, the participants indicated the "*grippiness of the snow*" on a scale ranging from −3 to +3, where −3 corresponded to grippy and +3 indicated slippery. The participants rated these characteristics in the upper and lower part of the course separately. The mean and standard deviation represented in the table are these two sections' averages.

Snow conditions

Snow characteristic	Pre-test	Acquisition day 1	Acquisition day 2	Acquisition day 3	Retention
Grippiness	−1.12 (1.4)	−0.86 (1.3)	−0.89 (1.4)	−0.78 (1.6)	−0.46 (1.8)
Iciness	−1.29 (1.3)	−1.56 (1.2)	−1.39 (1.3)	−1.78 (1.2)	−1.16 (1.6)
The homogeneity of the slope conditions	0.73 (1.8)	0.44 (2.1)	0.39 (1.8)	0.91 (1.8)	1.40 (1.7)

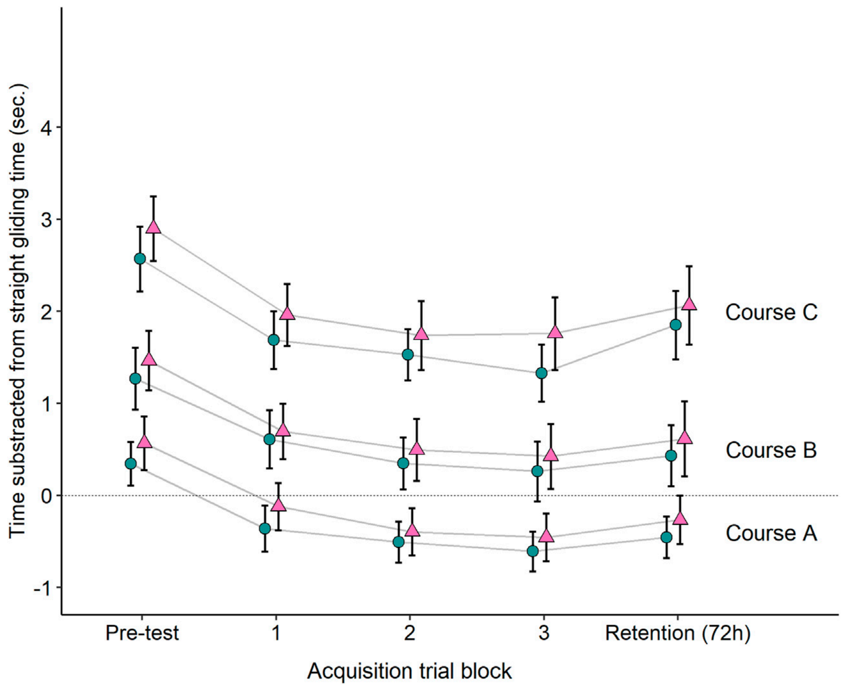

FIGURE 3
Sample means and 95% confidence intervals for the blocked (red triangle) and the interleaved (blue circle) in courses A, B and C. Performance was computed by calculating the average time the participant achieved for each course and subtracting it from the mean of his or her straight-gliding time on that day. A lower score, therefore, indicates a better performance. The dashed black line depicts when the performance was equal to the straight-gliding performance. To analyze the acquisition, the runs were numbered in the three courses from 1 to 12. We then placed 1–4 into Acquisition trial block 1, 5–8 into Acquisition trial block 2 and 9–12 into Acquisition trial block 3. Please note that not all skiers completed all the training sessions.

predicting retention revealed a main effect of Course, [F (2, 117.22) = 12.21, $p < 0.001$], when controlling for pre-test performance. This main effect revealed that the participants tended to ski the courses with the shortest offsets (Course A) faster than both other courses, which had larger offsets (Courses B and C). However, no main effect of Group was observed, [F (1, 72.82) = 0.33, $p = 0.570$], when controlling for pre-test performance. The magnitude of difference was only 0.11 s between the interleaved [M = 0.46; 95% CI (−0.06, 0.99)] and the blocked group [M = 0.58; 95% CI (0.04, 1.11)], adjusting for the magnitude of the same difference between the groups at pre-test. No higher-order interactions involving the Group variable were found: Group x Course, [F (2, 116.65) = 0.48, $p = 0.618$]; Pre x Group x Course, [F (2, 101.19) = 1.13, $p = 0.327$]. Hence, our data did not provide evidence for statistical significant group differences in retention in any courses, even when controlling for pre-test performance.

4 Discussion

The present study is one of few studies that have addressed the contextual interference effect with skilled learners in a complex task. To test the contextual interference effect, we set three different slalom courses and arranged the trials in these courses differently for the two groups. The participants in the interleaved group practiced each of the three slalom courses each training day in an interleaved order, whereas the blocked group trained the three courses on separate days in a blocked format. We hypothesized that interleaved practice would suppress performance during skill acquisition compared to blocked practice and that interleaved practice would improve retention performance. Contrary to our hypothesis, the data showed that interleaved practice did not significantly suppress acquisition performance or improve retention performance. In other words, our study did not reveal the contextual interference pattern previously reported in the motor learning literature. Both groups improved substantially during the intervention, but no reliable difference between the groups was observed.

The result of this study conflicts with the substantial body of research that has found the contextual interference effect to be present in a wide range of different laboratory tasks (e.g., Shea and Morgan, 1979; Magill and Hall, 1990; Simon and Bjork, 2001). A simple explanation for the divergence of this result from most scientific findings is that the skill level of our participants was considerably higher, and the skill type was more complex than in most previous studies on the contextual interference effect in motion tasks. In accordance with this view, a study with comparable characteristics to our study that addressed the contextual interference effect with skilled performers did not find that interleaved practice enhanced retention compared to blocked practice (Buszard et al., 2017). These researchers only found an advantage of interleaved over blocked practice in transferring the skills to competition performance. Therefore, gains in retention may not occur for skilled performers learning complex tasks following interleaved practice. However, this explanation conflicts with the findings of Hall et al. (1994), who found that interleaved practice improved retention for skilled batters compared to blocked practice. It is critical to note that this study manipulated the contextual interference between variations of the same skill (i.e., learning to bat in response to three different pitches) instead of manipulating it between skills like Buszard et al. (2017). Therefore, it could be that improvement in retention following interleaved practice will only appear for skilled performers if the manipulation occurs between variations of the same skill. However, this interpretation conflicts with our data pattern because we also performed the manipulation between variations of the same skill.

An alternative perspective on our results pertains to the characteristics of the skill used in our study. Alpine skiing is a continuous skill that operates heavily on feedback control mechanisms (for example, reacting to incoming visual and tactile information) entering the system to regulate motion while skiing through a slalom course (Diedrichsen and Kornysheva, 2015). Because of the long duration of a run in skiing (>40 s), more sensory information is potentially available and harnessed during the execution of the skill compared to the execution of discrete skills, which last for a much shorter time (Lee and Genovese, 1988, Lee and Genovese, 1989). The continuous characteristic and long run duration let participants evaluate their performance during execution and allow for rapid adjustments early and repeatedly during a run to sustain high-performance levels. This type of skill contrasts with discrete skills that have a shorter duration and, therefore, would not allow such adjustments during the run based on sensory feedback acquired during execution. Following this reasoning, with continuous skills, any potential interference from switching between courses may not be as influential because the learner may have sufficient time to adjust their performance during a trial. Although this explanation may contradict previous research that has observed the contextual interference effect with continuous skills, such as bimanual learning task (Tsutsui et al., 1998; Pauwels et al., 2014) and snowboarding turns (Smith, 2002), to our knowledge, no study has examined continuous tasks with skilled performers. From a challenge-point framework (Guadagnoli and Lee, 2004) point of view, it could be argued that the extensive stream of sensory signals that performers receive during skill execution is more interpretable and informative for skilled than for novice learners. Hence, skilled participants might better understand the feedback they get during a trial, allowing them to make necessary adjustments to accommodate optimal performance more effectively than novice learners. In effect, interleaved practice will impose different effects on performers with different skill levels that learn continuous tasks: for beginners, it will create favorable conditions for learning, but for skilled learners, it might not create stimuli sufficiently different from regular practice. This account may explain why Smith (2002) provided evidence for improved retention for beginners learning snowboarding turns, whereas our data did not support such a relationship. Therefore, future studies should further address the contextual interference effect for continuous tasks with skilled performers and primarily address the role the level of stimulus has on the contextual interference effect.

Another reason the contextual interference effect did not appear in the present study could be that the difference between the three slalom courses was not sufficiently large to probe the contextual interference effect. Although contextual interference research does not precisely detail the type or magnitude of contrast between tasks necessary to produce the contextual interference effect (Ramezanzade et al., 2022), this scenario is a potential limitation that needs consideration when evaluating this study. We maximized the offset differences that were within reason for the selected gate distance. Specifically, we sought to find a balance between the need for maximal differences while allowing for active pumping within the space constraints of the skiing hall. Previous research has also shown that changes in gate offset (of the magnitude we used in our study) significantly impact the skiers' technique and tactics (Spörri et al., 2012; Gilgien et al., 2015; Gilgien et al., 2021), providing evidence that the gate offset variation we chose adequately created contextual interference. However, it may be that the stimulus effect of the three courses changed during the intervention, such that a participant who got better at pumping needed to execute this skill in each course with a higher frequency or a different line selection than before the intervention. Consequently, the courses may have changed their impact on skiers' technique and tactics because the participants improved during the intervention. If so, the blocked group may also have experienced some interference each day, which may explain why we did not observe a contextual interference effect.

It is also conceivable that the long time that elapses between runs in typical alpine skiing sessions and in our study may have impacted the results. Participants used approximately 8 min between trials to ride the lift to the top and prepare themselves for a new run. This inter-trial interval is significantly longer than the inter-trial interval used in laboratory tasks, where discrete skills were tested (Barreiros et al., 2007). It may be that the time between trials was so long that athletes forgot and lost connection between trials, which is suggested to be one of the mechanisms causing the contextual interference effect (Lee and Magill, 1983, 1985). This interpretation similarly relates to the new theory of disuse (Bjork and Bjork, 1992). This theory assumes that lengthening the spacing between trials may increase forgetting yet enhance learning by reducing the retrieval strength of memory before every trial. In this view, both the interleaved and the block group may have experienced favorable conditions for skill learning due to the long time between trials. Suppose this explanation hindered any contextual interference effect from coming into place in our study. In that case, the contextual interference effect might never be present in alpine skiing due to the long time required to transport the skiers back to the start of the racetrack and establish the inter-run recovery needed. Alpine ski racing causes acute fatigue, requiring a break to recover between runs to avoid declining performance during the session due to accumulated physical and psychological fatigue (Turnbull et al., 2009; Ferguson, 2010). However, future investigations should examine whether the length of the inter-trial time affects contextual interference in general and especially as related to complex continuous skills.

A further point for discussion is that this study took a replacement approach to perform the training, whereby participants replaced their regular ski training entirely with that offered in the experiment. This strategy allowed us to minimize the number of intervening factors (for example, maturation and stress) during the experiment. By contrast, previous studies on contextual interference with skilled performers have performed the experiment by adding extra practice to the participant's regular training (Hall et al., 1994; Buszard et al., 2017). Consequently, the experiment often spans multiple weeks. Based on the evidence that distributing practice over an extended period can benefit learning (Lee and Genovese, 1988), the different approaches to examining contextual interference with skilled performers may be one reason for the observed differences between the studies.

Finally, we would like to consider two alternative interpretations for why we did not observe the contextual interference effect. The first reason is that interleaved practice does not alter task difficulty for these complex skills and this group of learners (Farrow and Buszard, 2017). This account posits that contextual interference is missing in this context unless an assessment of learning adopts a transfer criterion for learning. Unfortunately, we could not establish a transfer test for this study due to various constraints (e.g., access to the skiing hall). Therefore, an interleaved practice may improve learning, but the study could not capture this aspect of learning with the chosen design. In line with others (Buszard et al., 2017; Farrow and Buszard, 2017), we recommend that future studies on the contextual interference effect include transfer tests to understand better the contextual interference effect for complex tasks and skilled learners. The other explanation is that the contextual interference effect is usually more reliably observed with tasks with solid visual requirements (Apidogo et al., 2021; Schöllhorn et al., 2022). This account may explain why (Hall et al., 1994) observed improved retention in the batting task that required batters to perceive the type of throw for each trial, whereas Buszard et al. (2017) and we did not observe this relationship.

There are several potential caveats that should be considered when evaluating the findings of this study. First, this was a real-world learning study where groups of skiers from different ski clubs and academies trained together. Although this may have enhanced the ecological validity of the study because it mimics the skiers' regular training, we cannot eliminate the possibility that interactions between the skiers may have influenced the results. In general, the participants were quite spread around the hill during the experiment, but they could observe each other at the start or from the chairlift. Another point to consider is that, although we did everything to create proper and stable conditions, variation in the courses or conditions is inevitable, even in the indoor skiing hall.

5 Conclusion

To conclude, the unique strength of this study was the approach adopted to examine contextual interference in a complex sport with skilled participants. We recruited many skilled participants by creating a training intervention that targeted a specific skill the participants were willing to invest time and effort to improve. In contrast with the substantial body of literature on the contextual interference effect, our data did not provide support for the presence of the contextual interference effect using an interleaved training design. Some explanations for why we did not find support for the contextual interference effect include the skill level of our participants and the continuous and complex characteristics of the task. It is also essential to consider whether the manipulation was sufficiently large to create contextual interference. Even though our data did not support the contextual interference effect, we do not suggest that coaches should de-emphasize the importance of variability and changing courses in their training with alpine skiers. For example, frequently switching between different courses is suggested to be an effective strategy to enhance retention and transfer of skills in this sport because it mimics the competition environment (Farrow and Buszard, 2017). However, the effect may lag in time and not become apparent until several years of practice have been completed. We also provided evidence that interleaved practice did not degrade performance during acquisition. Therefore, coaches can safely employ interleaved practice training in alpine ski racing. Because many factors affect contextual interference in complex tasks with skilled performers, future research should continue studying the contextual interference in naturalistic environments, involving continuous tasks and skilled performers.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by The Human Research Ethics Committee of The Norwegian School of Sport Sciences. All participants provided written informed consent prior to the study. Where participants were less than 15 years of age, informed consent was provided from their parents/guardians.

Author contributions

CM, PH, RR, and MG contributed to the study's design, data collection, and manuscript writing. CM performed the data analysis and statistics of the data. CM wrote the first manuscript version, and CM, PH, RR, and MG contributed to the revision and final approval of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbioe.2022.966041/full#supplementary-material

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EDITED BY
Nicola Francesco Lopomo,
University of Brescia, Italy

REVIEWED BY
Juri Taborri,
University of Tuscia, Italy
Emilia Scalona,
University of Brescia, Italy
Paolo Perego,
Politecnico di Milano, Italy

*CORRESPONDENCE
Daniel Debertin,
daniel.debertin@uibk.ac.at
Peter Federolf,
peter.federolf@uibk.ac.at

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Quantitative downhill skiing technique analysis according to ski instruction curricula: A proof-of-concept study applying principal component analysis on wearable sensor data

Daniel Debertin[1,2]*, Felix Wachholz[1], Ralf Mikut[2] and Peter Federolf[1]*

[1]Department of Sport Science, University of Innsbruck, Innsbruck, Austria, [2]Institute for Automation and Applied Informatics, Karlsruhe Institute of Technology, Karlsruhe, Germany

Downhill skiing technique represents the complex coordinative movement patterns needed to control skiing motion. While scientific understanding of skiing technique is still incomplete, not least due to challenges in objectively measuring it, practitioners such as ski instructors have developed sophisticated and comprehensive descriptions of skiing technique. The current paper describes a 3-step proof-of-concept study introducing a technology platform for quantifying skiing technique that utilizes the practitioners' expert knowledge. The approach utilizes an inertial measurement unit system (Xsens™) and presents a motion analysis algorithm based on the Principal Movement (PM) concept. In step 1, certified ski instructors skied specified technique elements according to technique variations described in ski instruction curricula. The obtained data was used to establish a PM-coordinate system for skiing movements. In step 2, the techniques *parallel* and *carving turns* were compared. Step 3 presents a case study where the technique analysis methodology is applied to advise an individual skier on potential technique improvements. All objectives of the study were met, proving the suitability of the proposed technology for scientific and applied technique evaluations of downhill skiing. The underlying conceptual approach - utilizing expert knowledge and skills to generate tailored variability in motion data (step 1) that then dominate the orientation of the PMs, which, in turn, can serve as measures for technique elements of interest - could be applied in many other sports or for other applications in human movement analyses.

KEYWORDS
alpine skiing, biomechanics, inertial measurement unit, principal component analysis, coordination, human movement, kinematics, winter sport

Introduction

Downhill skiing is a very popular but also very demanding sport (Hébert-Losier et al., 2014)—particularly in terms of coordinative and adaptive motor control skill requirements. *Skiing technique* represents the complex coordinative movement pattern needed to not only control and direct the large forces acting on and in the skier's body (LeMaster, 2010), but also needed to cope with changing environmental conditions such as varying snow type, visibility, slope gradient, terrain unevenness etc. (Skilehrerverband, 2019).

Previous research, where skiing technique assessments played a role, was often motivated by the goal of understanding injury mechanisms (Urabe et al., 2002; Krosshaug et at., 2007; Pellegrini et al., 2018; Promsri et al., 2019), prevention of injuries (Spörri et al., 2017), improvement of racing performance (Roetenberg et al., 2009; Reid, 2010; Federolf, 2012; Hébert-Losier et al., 2014; Robert-Lachaine et al., 2017), and some studies assessed fundamental (bio-)mechanical aspects of skiing (Müller, 1994; Müller and Schwameder, 2003; Müller et al., 2005;, 2010; Klous et al., 2012; Meyer, 2012; Lind and Sanders, 2013). Despite these numerous investigations, the scientific understanding of many aspects of skiing technique is still incomplete. Moreover, the complexity of the skiing movements and the inhospitable environment pose particular challenges for adequate measurement technologies and hamper quantitative evaluation (Klous et al., 2010).

In contrast, practitioners, e.g. the ski schools or ski instructor associations, have developed structured and comprehensive descriptions of skiing technique. In particular, many ski instructor associations contrived instruction curricula to teach beginners how to ski (Skischulverband, 2015; Skilehrerverband, 2019), in most cases with clearly defined milestones, e.g. the "parallel turn" (side-skidding with parallel ski control) and the "carving turn" (skiing on the ski edges without side-skidding). Moreover, the curricula also describe specific technique modifications/ elements, for example, skiing in a forward or in a backward leaning position, skiing with or without pronounced vertical motion, turning with inward leaning versus turning with an upright upper body, etc. (LeMaster, 2010). Licensed ski instructors are not only required to recognize the techniques and technique elements in their clients' skiing to advise on potential improvements, they are also required to be able to demonstrate them themselves. Unfortunately, the expert knowledge that the practitioners have developed so far remains a qualitative description of skiing technique and researchers were only marginally able to utilize the expert knowledge of practitioners (Loland, 2009). The vision for the current project was therefore to establish a measurement and data analysis platform that allows to quantitatively assess skiing technique in such a way that it utilizes and is compatible with the approach and knowledge of expert ski practitioners.

Wearable sensor technology based on inertial measurement units (IMUs) (Kröll, et al., 2015; Fasel, et al., 2016) provides a first building block for the envisioned technology platform. Specifically, we utilized the commercially available Xsens™ system which had already been tested and validated for human movements recording for laboratory (Al-Amri, et al., 2018; Teufl et al., 2019) as well as for on-snow environments (Krüger and Edelmann-Nusser, 2010; Supej, 2010). IMU technology offers the advantage of instant and direct data availability for processing (Spörri, 2012), in contrast to other data acquisition technologies, for instance, the optical video reconstruction from panning, tilting and zooming cameras (Mössner et al., 1996; Nachbauer et al., 1996) or from fixed camera systems such as Vicon™ (Klous et al., 2010; Spörri et al., 2016) or Qualisys™ (Reid, 2010). The second building block for the envisioned technology platform is a data analysis algorithm based on a principal component analysis (PCA) (Troje, 2002; Daffertshofer et al., 2004). The specific approach introduced in the current paper is conceptually based on earlier studies (Federolf et al., 2014; Gløersen et al., 2018), but does add new conceptual ideas.

The challenge addressed in the current study is the establishment of a procedure to utilize expert knowledge of the practitioners—in our case skiing instructors but our approach could similarly be utilized in other sports with practical expert knowledge on technique—to provide quantifiable data for the practitioners' qualitative descriptions of technique. In contrast to previous studies, the current study tailored the PCA output to specific technique elements of interest by beforehand creating an additional dataset whose variance is purposefully manipulated through having skiing instructors demonstrate specific technique features. Through this procedure, we can for the first time quantitatively assess skiing technique in a manner consistent with the technique descriptions of skiing experts. In summary, the current study represents a three-step proof-of-concept study. The goal of the first step was to obtain—through a PCA based on wearable sensor data—a coordinate system for skiing movements, which aligns with the movement descriptions used in the Austrian ski instruction curriculum (Skischulverband, 2015). Thus, we obtain objective measurement scales for skiing technique elements. The goal of the second step was to apply this movement evaluation system in an assessment of differences between the skiing techniques "parallel turn" and "carving" (Skischulverband, 2015). The goal of the third step was to demonstrate practical applicability of our method through comparing the technique of a ski instructor aspirant (good skier, but has not passed the instructor license exams yet) with the techniques of certified ski instructors.

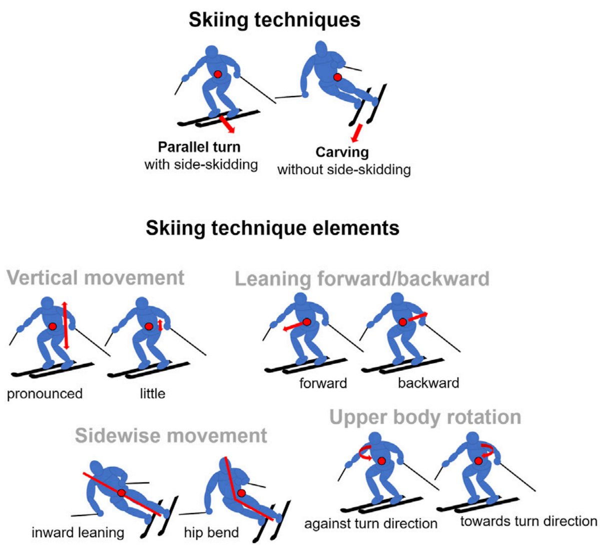

FIGURE 1
Schematics illustrating the main techniques of parallel and carving turns, as well as the involved skiing technique elements based on the descriptions in the Austrian ski instruction curriculum (Skischulverband, 2015) and demonstrated by the ski instructors within the study.

Materials and methods

Participants

Eight experienced and highly educated ski instructors (3 female, five male; M = 27.0 years, SD = 3.0) participated in the study. The main inclusion criterion was an active ski instructor license: half of the participants held a national and the other half a regional instructor license. Further inclusion criteria were age above 18, skiing experience of more than 10 years and more than 30 seasonal skiing days. Exclusion criteria were any recent injuries which might influence skiing abilities. The aspirant recruited for the third step of the study fit the same inclusion criteria with the exception of the active instructor license. All participants were informed about the background and the purposes of the study and provided written consent. The study was approved by the Board for Ethical Questions in Science of the University of Innsbruck (certificate 55/2019).

Study design

A coordinate system aligning with technique elements as described in the skiing curricula (step 1) can be obtained through a PCA when tasking the ski instructors with modifying their skiing according to eight distinct technique elements. Specifically, we instructed the skiers to use parallel turns as the base technique and to then modify this technique by forward versus backward leaning, pronounced versus little vertical movement, inward leaning versus hip bending, and rotating the upper body towards versus against the turn direction (Figure 1). The testing order of these four pairs of opposing technique instructions was randomized between participants. In addition, for step 2, the instructors were asked to ski the techniques parallel turn and carving turn (Figure 1) precisely according to the descriptions in the Austrian ski instruction curriculum (Skischulverband, 2015). Further instructions were to ski with equal turn radii and to aim for a smooth and natural movement execution. Each technique and each technique element were skied in one separate run of at least seven complete turns. Prior to testing, skiers had performed several warm-up runs. Before each run, sensors were calibrated by walking a short distance in ski boots over a flattened area of the ski piste and standing in neutral position. The measurements were carried out at the ski resorts Axamer Lizum and St. Christoph am Arlberg, Austria on even and moderately steep slopes (M = 23.1% gradient, SD = 0.6). The testing period was half a day for each participant. Weather and snow conditions were similar and allowed for easy controllable skiing.

Data acquisition

Kinematic data was recorded using Xsens™ MVN Technology (Xsens Technologies B.V., Enschede, Netherlands). The hardware (Firmware Version 1.2.0) consisted of 17 inertial measurement units (gyroscopes, accelerometers and magnetometers) operating at 240 Hz, which were placed at prescribed body positions within a tight Lycra suit (Figure 2A). Foot sensors were placed on the outside of the ski boots above the foot arch, wrapped in foil to protect them against humidity and cold, and attached with duct tape. The Xsens™ software (Version 2019.2) postprocesses the recorded sensor raw data by combining all available information using Kalman filters and biomechanical constraints. The calibration process ensures the sensors' position alignment with the implemented human model (Figure 2B), which is based on 23 rigid segments. The software outputs 3D segment and estimated center of mass (COM) coordinates in relation to the pelvis origin. In order to visually compare reconstructed poses with the original movement, every trial was additionally filmed using a GoPro Hero 8 camera (GoPro Inc., San Mateo, United States).

Data analysis

The current study analyzed 3D segment position data (represented by segment origin: proximal joint position). Data

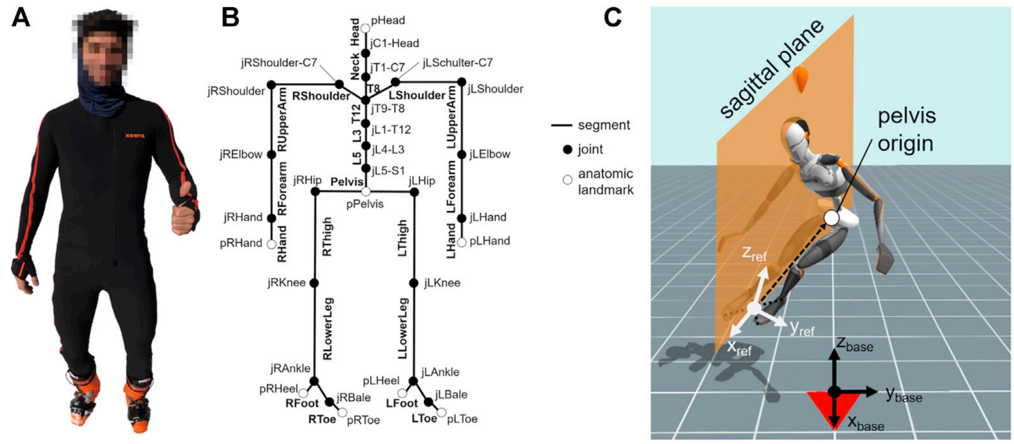

FIGURE 2
(A) Volunteer wearing the Xsens™ suit for skiing: sensors on the feet were attached to the ski boots from the outside; **(B)** body model with extracted reference points for body segment positions; **(C)** reconstructed avatar (adopted from Xsens™ software) with reference coordinate system.

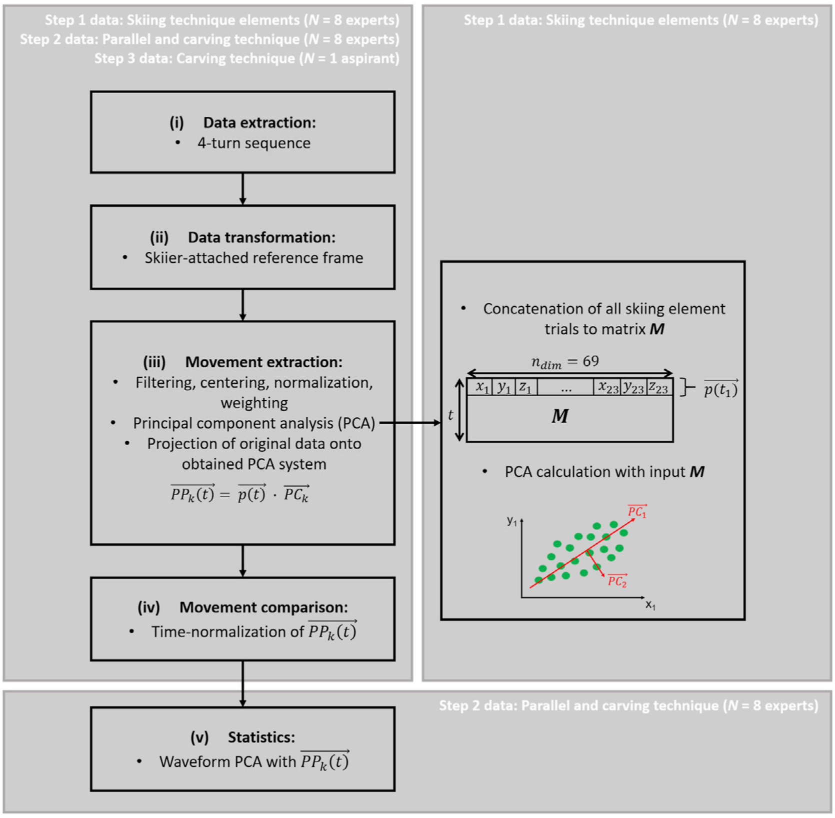

FIGURE 3
Flowchart of data analysis steps from data extraction of four consecutive turns, to transformation into skier-attached reference frame, movement extraction by principal component analysis (PCA), comparison through time-normalization and statistical evaluation. The PCA is performed for the skiing technique element trials (step 1 data) and the skiing technique trials (step 2 and 3 data) are projected onto the obtained PCA system.

processing was coded in MATLAB R2019b (The MathWorks, Natick, Massachusetts, United States). Data analysis (Figure 3) consisted of the five main steps: (i) identification of turn cycles and extraction of four consecutive turns; (ii) transformation of position data into a skier-attached reference frame; (iii) partial movement extraction by PCA; (iv) time-normalization of the turn data through interpolation; (v) statistical analysis to assess differences between carving and parallel turn waveforms. The following paragraphs provide details about these analysis steps.

(i) The turn sequences were determined through first setting up an interim reference frame with its origin in the midpoint of all toe and heel markers; its x-axis pointing towards the midpoint between the toe markers; the z-axis was the Xsens™-z-axis, which points vertically upwards against gravity; and the y-direction resulted from a cross product of x and z. Within this system, the transition between ski turns was determined as the time point when the COM's y-coordinate was zero (i.e. when the skier was upright on the skis). From each trial, four consecutive turns, a left-right-left-right turn sequence, were extracted for analysis.
(ii) The skier-attached reference frame (Federolf et al., 2014) was then obtained through a coordinate rotation around x, such that the x-y-plane contained the center of the pelvis (Figure 2C). Thereby the resultant coordinate system inclines with the skier into the turn.
(iii) The time series of the 3D segment positions of the 4-turn sequence of each trial were then filtered with a 4th-order, 50 Hz low-pass Butterworth filter, centered by subtracting the mean posture of the skier, normalized to mean Euclidian distance (Federolf et al., 2008; Federolf et al., 2013) to allow comparisons between subjects, and weighted using De Leva's relative segment masses (De Leva, 1996). Then, the trials in which the skiers had performed the eight distinct technique elements (step 1), were concatenated to form a single input matrix for the PCA [(8 participants * 8 trials * time points) x (23*3 segment positions)]. The data from the parallel and carving turns (step 2) and from the case study (step 3) were not used for calculating the PCA, but were later projected onto the PCA system obtained from step 1. The data pre-processing steps and the PCA calculation, as described in the current paragraph, were performed using the PManalyzer, a publicly available software toolbox (Haid et al., 2019). The PCA provides a new coordinate system spanned by the eigenvectors (PC-vectors) of the covariance matrix. Each PC-vector represents a specific pattern, how a given body configuration deviates from the mean posture. We refer to these partial movements represented by each PC-vector as "principal movements" (PMs) (Federolf et al., 2013; Federolf, 2016). The first few PMs explain the greatest amount of variability in the data set, and since we produced large variability by instructing the skiers to ski specific technique elements in opposite extremes (step 1), we achieve an alignment of the PC-vectors with the given technique specifications. We can visualize each PM as animated stick figures by a retransformation onto the original system (Supplementary Material). By transforming the original data onto the PMs, time series of principal positions (PP(t)s) are obtained. The PP(t)s provide measures for the skiers' movements expressed according to the PMs. Technique differences between parallel and carving turns could thus be quantified through projecting these turns also onto the PM-coordinate system.
(iv) As a last data processing step, the PP(t) obtained from the 4-turn sequences were time-normalized by interpolation to 100 data points per left-right turn sequence. Thereby, comparisons between different skiing technique elements, different techniques (parallel vs. carving) and different skier expertise (instructor vs. aspirant) were enabled.
(v) The time-normalized PP(t) waveforms could then be averaged for graphical display and statistically tested for differences between the parallel and the carving technique.

Statistics (parallel versus carving skiing technique)

To determine technique differences between parallel and carving turns, we assessed differences in the shape of the PP(t) waveforms. Thereto, the PP(t) graphs were submitted to a waveform-PCA, i.e. inputs were the 100-point waveform shapes (Mohr et al., 2021). The scores of the first component, i.e. the main feature producing waveform variability, served as dependent variable and was statistically evaluated.

All statistical calculations were conducted using the software Jamovi 1.1.9.0 (The jamovi project, 2021). The Shapiro-Wilk test confirmed normality for all PP(t) scores. Therefore, we report the results of paired t-tests with Cohen's d quantifying the effect size. Due to the small sample size ($N = 8$) we further corroborated all statistically implied conclusions through the corresponding non-parametric tests (Wilcoxon signed-rank test), for which we found no discrepancies to the t-test results. Additionally, a Holm-Bonferroni-correction (Holm, 1979) was applied to account for the fact that six t-tests (we considered the first six PP(t)s since they were visibly affected by the technique elements and represented 99% of the postural variance) were conducted. In all tests we used $\alpha = 0.05$ as the base threshold for statistical significance. We refer to effect sizes of $d > 0.8$ as strong effects (Cohen, 1992).

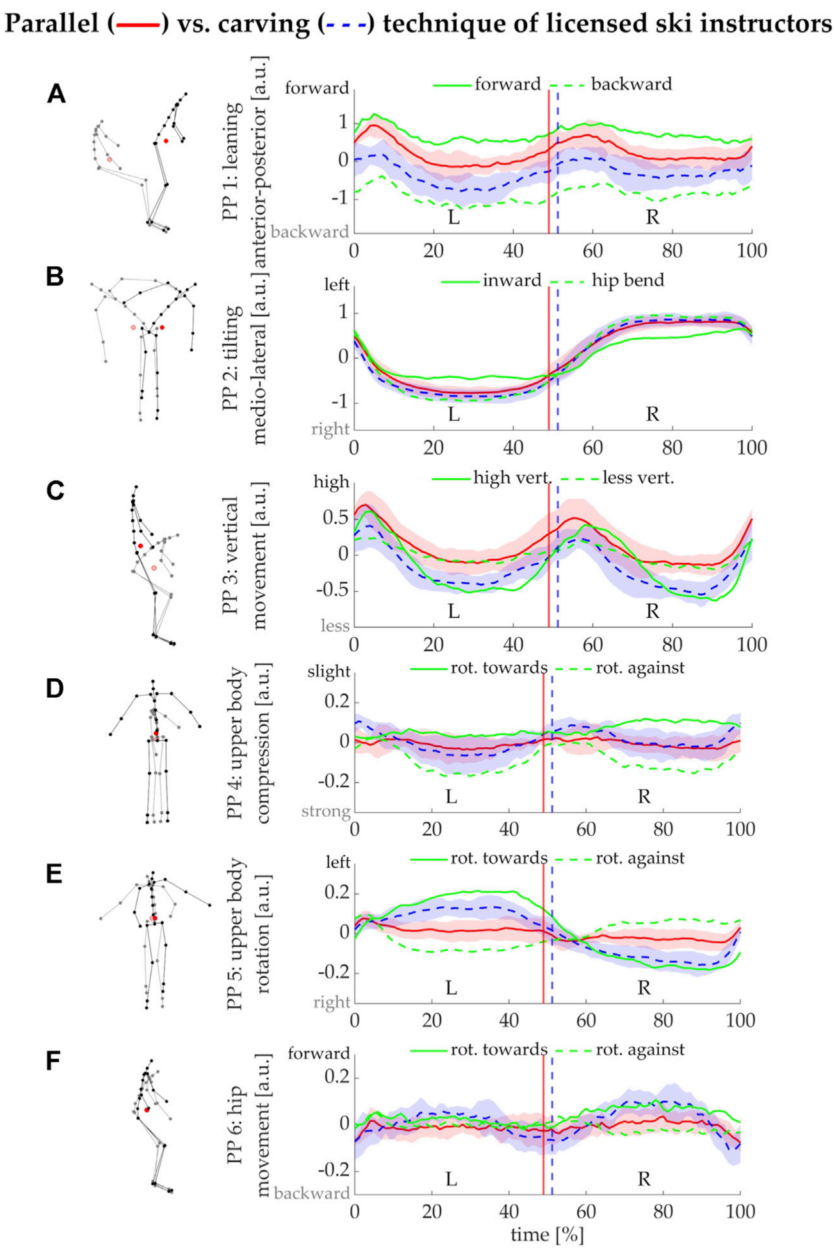

FIGURE 4
Left: stick figure representation of the first six principal movements (PMs). Right: time series representation for each principal movement position PPk(t) [k = 1.6] **(A–F)** interpolated to 100% of a left(L)-right(R) ski turn cycle. For each PM, the instruction trials that caused the largest differences in the PP(t)—e.g., for PM1 the instructions to lean forward or backward—are displayed as continuous and broken green lines (means over all turn cycles of all volunteers). The red and blue lines and shaded areas represent the mean and standard deviations obtained from the parallel and carving turns of all the volunteers, respectively. Vertical lines indicate the mean time point of transition from L to R turn.

Case study of ski instructor aspirant

The volunteer was asked to perform carving turns according to the skiing curriculum (Skischulverband, 2015) on the same slope where the ski instructors had conducted their trials. Similar to step 2, the data was projected onto the eigenvectors obtained from the analysis of step 1. PP(t) results were graphically visualized and compared to the mean trajectories of the certified ski instructors.

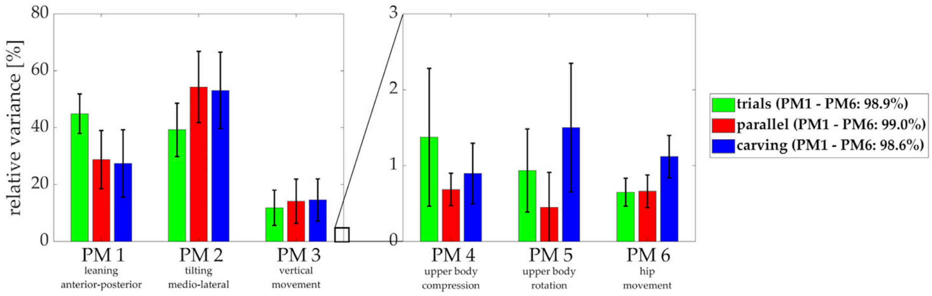

FIGURE 5
Relative variances explained by the first six principal movements (PMs) for the trials with instructed technique variations (green bars) [this is the data for which the PCA was calculated in step 1] and relative variances for the parallel (red) and carving turns (blue) analyzed in step 2 [these data were projected onto the PC-eigenvectors obtained in the analysis of step 1].

Results

The PM-coordinate system for skiing technique

The coordinate system produced by the PCA, particularly axes PM1, PM2, PM3, and PM5, aligned well with the changes in posture produced by the specific technique instructions. The first eigenvector (PM1) captured changes in posture associated with anterior-posterior body positioning (stick figure in Figure 4A). Accordingly, PP1(t) can serve as a measure for quantifying forward (continuous green line in Figure 4A) or backward leaning (broken green line) in the skiing technique. PM1 quantified 44.9% of all postural variances observed in the specific technique trials (green bars in Figure 5). PM2 captured a medio-lateral tilting (moving away from the sagittal plane) of the upper body and, accordingly, the technique instructions of inward leaning as opposed to hip bending (green lines in Figure 4B) produced the largest differences in PP2(t) waveform shape. PM2 represented 39.2% of the postural variances of the technique trials. PM3 represented 11.8% of the variance and captured knee flexion together with a crouching motion of the upper body. The instruction to ski with large versus little vertical movement produced the largest differences in the PP3(t) graphs (Figure 4C). PM4 (1.4% of postural variance) captured a change in posture that appeared as upper body compression and arm motion in the stick figure representation. PM4 can be interpreted as a residual posture change arising from the linearization of anatomical movements. The instruction pair of rotating with as opposed to against the turn produced the largest differences in the PP4(t) graphs (Figure 4D). PM5 (0.9% of postural variance) captured upper body rotations and, accordingly, the instruction to rotate with or against the turn produced the largest differences also in PP5(t) (Figure 4E). Finally, PM6 captured a hip positioning and slight crouching, but represented only 0.6% of the variance. PP6(t) also showed the largest differences for the instructions of rotating with versus against the turn (Figure 4F).

Parallel and carving techniques assessed in the PM-coordinate system

The first six PMs together covered 99.0 and 98.6% of the postural variance of the parallel and carving techniques, respectively (Figure 5). Interestingly, for both techniques the PM2 movement (medio-lateral tilting) now contributed more to the overall postural variance than PM1 (anterior-posterior leaning).

Differences in the PP(t)-waveform shape between the techniques appeared for PM1, PM3, PM4, PM5, and PM6, demonstrating that carving involves more backward leaning (PM1: t (7) = 4.3, p = 0.003, d = 1.53) and overall a more crouched position (PM3: t (7) = 4.8, p = 0.002, d = 1.68) than the parallel turn technique. Also, carving is performed with rotating the upper body with the turn, while the parallel turn shows upper body rotation against the turn (PM5: t (7) = 6.0, $p < 0.001$, d = 2.13). Lateral tilting (PM2) did not differ significantly between techniques (p = 0.363). The carving technique also showed more movement in PM4 (t (7) = 3.0, p = 0.019, d = 1.07) and PM6 (t (7) = 3.1, p = 0.018, d = 1.08) compared to the parallel turn, for which a neutral positioning with relatively little changes throughout the turns were found in both movement components.

Case study: Individual skiing technique assessment

Figure 6 visualizes the assessment of the individual technique of the volunteering instructor aspirant in comparison with the combined carving turn data of the

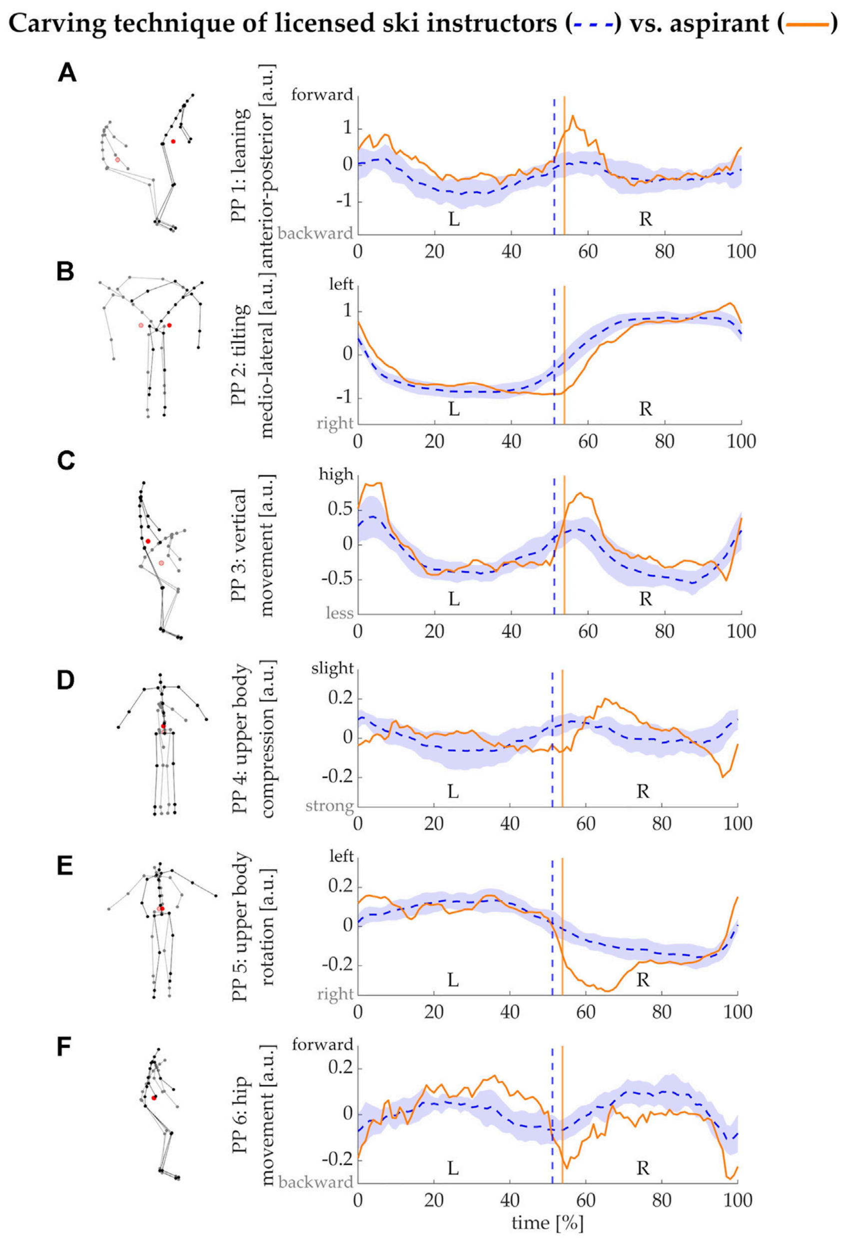

FIGURE 6
Case study: comparison of the individual technique of a specific skier with reference data from the ski instructors. PM1-6 **(A–F)**, visualized by the stick figures and displayed by the PP(t) series are adopted from Figure 4 for all carving turns of the skiers with active ski instructor license (blue lines and shaded areas for mean and standard deviation). The recorded carving turns of the aspirant are projected onto the same PM-coordinate system (orange lines).

licenced instructors. We can provide the feedback, that the candidate showed more vertical motion (Figure 6C) in combination with more forward movement (Figure 6A) when initializing the new turns compared to the reference skiers. Particularly in the first half of the right turn, pronounced rotation of the upper body is visible (Figure 6E), which the peers do not show. Also, more pronounced hip movements are visible (Figure 6F). Overall, due to the pronounced body actions (vertical motion, rotating into the turn) the movement appears jerkier compared to the relatively smooth motion seen in the instructor data. Based on these particular turns, we would recommend to the aspirant to practice carving turns with less pronounced vertical motion during turn initiation (this will likely also reduce the pronounced forward motion in PM1) and to practice with less upper body rotation.

Discussion

The objectives of the current proof-of-concept study were 1) to develop a measurement methodology for skiing technique based on the approaches and technique descriptions found in ski instruction curricula; 2) use this methodology to evaluate differences between the parallel turn and carving turn techniques; 3) in a case study, evaluate technique differences between an individual skier and reference data obtained from ski instructors. We accomplished these goals through performing a PCA on data obtained in trials where we asked experts to perform specific technique elements. The results shown in the current paper demonstrate and prove suitability of the conceptual approach for the purposes of technique evaluations in downhill skiing.

Conceptual considerations

This approach is not limited to skiing, but could be applied in many other sports where qualitative technique descriptions are available. It could also be applied in other contexts of human movement analysis to quantify specific, so far only qualitatively described behavior. Examples could be quantification of body language in psychology, quantification of movement patterns in work place environments, or automated behavior recognition problems in human-robot interactions.

Technique elements in skiing

Variations in the forward-backward positioning of the body over the ski is a technique variation that skilled ski instructors can demonstrate routinely and it leads to substantial variance in the overall body posture. Therefore, not surprisingly, this technique element defined the first principal component eigenvector and thus PM1. Within the ski turns, we observed that during the early phase of the turn (turn initiation), a forward movement can be observed in all trials. During the second half of the turns (steering phase) the skiers' bodies shifted slightly backwards. These findings are consistent with ski instruction curricula (Skischulverband, 2015; Skilehrerverband, 2019). The ability to quantify forward-backward leaning provides several opportunities for future research, for example, extensive backward leaning is frequently observed in novice skiers and is often considered a mistake since backward positioning makes control of the skiing motion more difficult (Skilehrerverband, 2019). Our methodology for studying skiing technique might make it possible to better understand the mechanisms leading to backward leaning in novices and might reveal which instructions or exercises could help novices to better gain control over their positioning. Additionally, backward leaning is also relevant from an injury mechanism and prevention perspective, since it increases the moments of force acting on the knee and increases strains on the anterior cruciate ligament (ACL) (Eberle et al., 2019; Raschner et al., 2001; Yoneyama and Okamoto, 2001; Yu et al., 2016; Zago et al., 2017a; Yoshioka et al., 2017; Zago et al., 2017;, 2019; Färber et al., 2019; Heinrich; Werner et al., 2021; Federolf, 2019). In several situations, backward leaning is an important contributing factor to an elevated injury risk (Bere, et al., 2011; Brodie et al., 2008; Heinrich et al., 2022).

The instruction pair "inward leaning into the turn" versus "hip bending" produced the largest differences visible in PM2. Contrary to the situation in PM1, however, the postural variance was here not mainly a consequence of the given instruction. Instead, large postural variance is produced by the skiing movements themselves during the left-right turn sequence, which require a leaning to the left and right, respectively. When explicitly instructed to lean into the turn and not to hip-bend, then the ski instructors were able to demonstrate this technique variation clearly enough to be detectable in PM2, but they still had to lean to the left and right, as is visible in Figure 4B.

The instructions to show pronounced or little vertical movement are another set of technique variations that ski instructors can routinely demonstrate. Accordingly, differences between these trials are clearly visible in PM3, which mostly captured the vertical motion. The corresponding graph in Figure 4C suggests, that the instructors could substantially reduce their vertical motion when asked to do so, however, in the data obtained in the current study, the skiers still showed some upward motion in the turn initiation phase. Mechanically, the vertical motion is believed to regulate the load/forces onto the skis. Therefore, future research where our technique measurements are combined with pressure insoles in the ski boots or with force plates in the ski binding would be interesting.

The instruction pair to rotate the upper body towards versus against the turn influenced all three remaining PMs (Figures 4D–F) analyzed in the current study. This was expected, since PCA produces a linear coordinate system and consequently, any rotation will necessarily affect several (at least two) PMs. PM5 is probably the best suited as a scale for this technique variation, since on the one hand, the stick figure representation comes closest to the expected posture variation, and on the other hand, the opposite instructions led to opposite behavior in the PP5(t) graph (Figure 4E).

In summary, all investigated technique variations demonstrated by the ski instructors volunteering in our study led to measurable differences in the PP(t) trajectories calculated based on this data. Investigation of more technique elements would be possible through analogue procedures.

Differences between the parallel and carving technique

A methodologic point to discuss before evaluating technique differences between parallel and carving turns is the question, whether it is justified to project data obtained from "carving" onto coordinate axes obtained from technique variations based on the "parallel turn" technique. Our data suggest that it was justified, since even for the carving turns, when projected onto our six PMs, 98.6% of the entire postural variance was explained (Figure 5). In comparison, for the parallel turns 99.0% of postural variance was explained, i.e. only marginally more. For both skiing techniques, the first six PMs together provided very close approximations of the skiers' movements.

Case study: Evaluation of an individual's technique

The case study results demonstrate applicability of the presented technique measurement approach for providing individualized feedback to skiers. The outlined case, an aspirant for the ski instructor exams, is an example where such feedback would be particularly useful: perception of one's own skiing can be misleading. Aspirants therefore often require and depend on the feedback of experienced instructors when they train required technique forms. Objective feedback on one's own technique through our approach and thus independent of an expert observer could create more opportunities for practice. In addition to the feedback in terms of the technique variations defined in ski instruction curricula, as described in the current paper, the PM approach can also provide feedback in form of animated stick figures. This might be useful, both, when the definitions of the specific technique elements are not entirely clear to an aspirant, or generally in ski instructor education to better recognize technique features in a skier.

Limitations

The small number of volunteers ($N = 8$) is a limitation of the current study. Recruitment into the study is limited, on the one hand, by the requirement of finding certified experts to volunteer; on the other hand, it is also a result of environmental conditions since unsuitable weather or snow conditions precluded testing on some days. Another limitation is that the quality of the results in the current study depends on the expert skiers' ability to demonstrate the instructed technique elements. In our opinion, the data suggests good agreement of the skiing techniques among the experts, suggesting that they were all able to properly execute the instructed techniques. It should be noted here, that all expert skiers in the current study were Austrian ski instructors. Skiing curricula and instructor education differ between countries, experts from other countries might therefore demonstrate the techniques differently or might differ in their execution of the parallel and carving turns.

Technical limitations arise from the chosen hardware and measurement principles. Particularly drift in the data is an issue. To minimize drift, recalibration was done after every downhill run. For the analysis of postural movements as conducted in the current study the Xsens™ device provided sufficient accuracy, however, it was not possible to extract the skier trajectory in an external coordinate system. For that purpose, combinations of an IMU-based sensor system with a global positioning system is likely necessary.

Regarding limitations in the data analysis algorithms, it should be noted, that PCA provides a linear coordinate system. Many forms of body segment movements, particularly rotations, project onto several PC-vectors. Specific PMs can serve as measures or as approximations for specific technique elements—as the current study shows—but they should not be misunderstood as the technique elements themselves.

Conclusion

The current proof-of-concept study accomplished a so far unsolved technological challenge: "how can skiing technique be quantified in accordance with experts' qualitative descriptions of skiing techniques?". Our solution provides objective measures for skiing technique, in which we utilized the expert knowledge of ski experts (ski instructors) and skiing curricula. We analyzed technique differences between two well-defined skiing techniques, parallel turns and carving, and we present a case study, how individual technique could be compared to reference data from other skiers to provide individualized feedback.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Board for Ethical Questions in Science of the University of Innsbruck. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

The study was conceived by PF and DD. Data collection was conducted by DD and FW. Data analysis including MATLAB coding was done by DD. PF and RM supervised the project. DD and PF prepared the first draft of the manuscript. All authors revised the manuscript and agree with the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbioe.2022.1003619/full#supplementary-material

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EDITED BY
Gert-Jan Pepping,
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Portugal
Ensar Abazovic,
University of Sarajevo,
Bosnia and Herzegovina

*CORRESPONDENCE
Tina van Duijn
tinavanduijn@gmail.com

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Assessment of water safety competencies: Benefits and caveats of testing in open water

Tina van Duijn[1]*, Kane Cocker[1], Ludovic Seifert[2,3] and Chris Button[1]

[1]School of Physical Education, Sport and Exercise Sciences, University of Otago, Dunedin, New Zealand, [2]CETAPS EA3832, Faculty of Sport Sciences, University of Rouen Normandy, Mont-Saint-Aignan, France, [3]Institut Universitaire de France (IUF), Paris, France

Drowning has been the cause of over 2.5 million preventable deaths in the past decade. Despite the fact that the majority of drownings occur in open water, assessment of water safety competency typically occurs in swimming pools. The assessment of water safety competency in open water environments brings with it a few difficulties, but also promises tremendous benefits. The aim of this position paper is to discuss the benefits and caveats of conducting assessments in open water environments as opposed to closed and controlled environments, and to provide recommendations for evidence-based practice. The first theoretical section discusses the effects of the environment and key variables (such as temperature and water movement) on various factors of assessment. These discussions are linked to the two perspectives of representative learning design (based on ecological dynamics) and information processing theory. The second section presents two pilot studies of relevance and provides practical implications for assessment of water safety competency. It seems that a combination of pool-based practice and open water education may be ideal in assessing aquatic skills competency. Assessment in open water presents clear benefits regarding validity, but often poses seemingly unsurmountable barriers, which providers may have reservations about in the absence of clear evidence. Hence this article provides a robust discussion about competency assessment and signals the practical importance of faithfully reproducing the environment in which skilled behavior is most relevant.

KEYWORDS

aquatic skills, environment, ecological dynamics, cognitive psychology, validity, outdoor, skill learning

Introduction

Drowning has been the cause of over 2.5 million preventable deaths in the past decade (UN General Assembly, 2021). It is responsible for more deaths than hepatitis or maternal mortality and close to that of malnutrition (World Health Organisation, 2022). The World Health Organisation (2021b) has made the provision of basic swimming and water safety skills a strategic priority for the next decade. In emergencies, such as drowning situations, skilled behavior can save lives, hence it is crucial that skills are assessed robustly (Chan et al., 2020). Skill assessment forms an integral part of any instructional program, so practitioners need scientific evidence base to inform assessment policy (Langendorfer and Bruya, 1995).

In general, the assessment of motor skill competency takes place in controlled and predictable environments where knowledge and skills are initially broken down and demonstrated in turn. For example, in a typical car driving test learners are first required to pass basic theory and visual function tests, then they are asked to perform some rudimentary driving maneuvers (e.g., emergency stop, reverse park, etc.), and finally they need to demonstrate they can drive safely in more realistic traffic conditions. Only once a rudimentary level of skilled behavior can be reliably demonstrated in controlled settings do practitioners go on to assess skill in more realistic (and challenging) natural environments. Relatedly, assessments of children's fundamental movement skills (such as running, jumping, and throwing) are historically undertaken in the absence of play or game-related contexts (Ng and Button, 2018). For reliability and safety reasons one may appreciate why skill assessments are typically undertaken in such a way, but it is not well known whether such movement assessment batteries can discriminate amongst different levels of performance (Cools et al., 2009).

In this article, we focus attention on the assessment of water safety competency. There is clearly a need for evidence-based recommendations on instruction and assessment of these skills, and "[…] a more encompassing and dynamic view of water competence and drowning prevention education that addresses the dynamic and complex nature of drowning" (Stallman et al., 2017, p. 25). Consequently, we shall explain some important theoretical considerations from the motor learning perspective to help underpin the limited evidence currently available. Then, we go on to describe two case studies that illustrate some of the challenges of assessing skills in open water. The aim of this position paper is to discuss the benefits and caveats of conducting assessments in open water environments as opposed to closed and controlled environments (i.e., swimming pools or flumes).

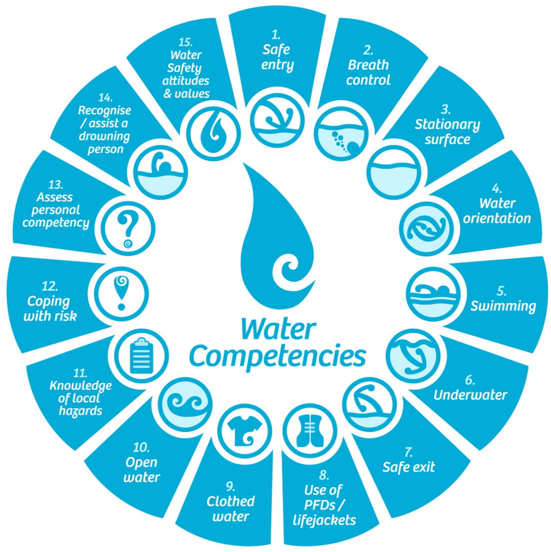

FIGURE 1
The 15 water competencies required to reduce the risk of drowning. Reproduced with permission of Drowning Prevention Auckland (https://www.dpanz.org.nz/courses/water-safety-for-children).

At least in developed nations, the assessment of swimming and water safety skills is typically undertaken in swimming pools, usually as part of education classes (Erbaugh, 1978; Moran et al., 2012; Stevens and NZCER, 2016; Di Paola, 2019; Chan et al., 2020). Swimming pools provide a seemingly "ideal" setting for competency assessments as the environmental conditions are relatively comfortable, stable, and reproducible (i.e., water temperature, currents, waves, depth, etc.). For example, Erbaugh (1978) showed that even when testing relatively unskilled individuals (i.e., 2–6 years old preschool children) it is possible to achieve high levels of inter-rater reliability when assessments are undertaken in a pool. However, introducing more variability in the water conditions of a swimming pool (such as waves) is likely to impact upon a learner's aquatic abilities. Indeed Kjendlie et al. (2013), showed that when open water-like conditions (i.e., waves) are simulated in a pool, the levels of skill competency are markedly lower. In their study, 66 11-year-old children performed identical tests in two different environments: a calm swimming pool and a simulated wavy environment (30–40 cm amplitude). The tests consisted of a 200 m swimming time trial, a 3 min floating test, a diving entry to the pool, and a rolling entry. The tests performed in the waves clearly showed a performance decrement (between 9 and 14% longer time to complete the swimming test and 21, 16, and 24% lower scores for rolling entry, diving, and floating tests, respectively). Kjendlie et al. (2013), highlighted the fact that children "should not be expected to reproduce swimming skills they have performed in calm water with the same proficiency in unsteady conditions during an emergency" (p. 303). To our knowledge no studies have compared learning of adults' performance of water safety-related competencies between

Background: Assessment of aquatic skills

Aquatic skill competency is much more than being able to swim (Langendorfer and Bruya, 1995). Stallman et al. (2017) have proposed 15 different fundamental aquatic skills that form the basis of aquatic skill competency assessments, with swimming being only one of 15 competencies (see Figure 1). Robust assessments of water safety skills should include a range of competencies such as getting into and out of water safely, floating, breath control, underwater swimming, and recognizing hazards for oneself and others.

different environments, and similarly with children the evidence-base is poor (Quan et al., 2015; van Duijn et al., 2021b).

Whilst swimming pools are the chosen location for swim lessons in most developed countries around the world, the majority of drownings happen outdoors (Quan et al., 2012). For example, out of 74 drownings in 2020 in New Zealand, the large majority (87%, $n = 65$) occurred in open water environments (Water Safety New Zealand, 2021). In the United States, open water drownings outnumber swimming pool drownings, because open water is the major drowning site for school age children, adolescents, and adults (Quan et al., 2008). In lower and middle-income countries, the main locations of drowning are ponds, lakes, rivers and ditches (World Health Organisation, 2014). As the range of external factors causing open water drowning (e.g., travel, work, flood-related disasters, etc.) is much wider than that of factors causing swimming pool drownings, the burden of open water drowning is much more difficult to quantify (World Health Organisation, 2022a).

To address the issue of assessment in naturalistic environments Hulteen et al. (2015), conducted a systematic review of field-based assessments for movement skill competency in lifelong physical activities. Only two published studies satisfied the inclusion criteria in relation to swimming or aquatic activities (Erbaugh, 1978; Zetou et al., 2014). In both studies, children under the age of 12 years were tested, and a swimming pool was used for the assessments. Whilst Erbaugh (1978) assessed several aquatic skills (water entry, front and back locomotion, breathing, kicking, underwater object retrieval), Zetou et al. (2014) only assessed backstroke. For both studies the inter-rater reliability of the assessed skills was high (Erbaugh, 1978: $r = 0.89–0.99$; Zetou et al., 2014: $r = 0.79$). Unfortunately, neither study considered the validity of the methods used nor whether the skills were as well produced in a different environment other than a swimming pool. To our knowledge this is the only published research investigating the effects of environment on the production of fundamental aquatic skills, and more evidence is urgently needed (Button, 2016). Furthermore, very little has been done to investigate the transfer of skills from controlled environments to real-life open water situations, which is arguably one of the biggest questions to be addressed in drowning prevention globally (Button and Croft, 2017; Guignard et al., 2020). Neither have the reliability and validity of aquatic skills assessment tools been tested with regards to predicting open water competence, risk of drowning or injury.

Summarizing thus far, water safety skills are typically assessed in swimming pools, yet they are arguably most required in open water (e.g., Lepore et al., 2015; Quan et al., 2015). Assessment of skills in pools may be misleading, as these skills are not assessed under the added pressure and mental stress that the natural environment can provide. Factors such as waves, currents, depth, visibility, temperature, submerged obstacles, surveillance, and many more set different environments apart. It would appear that water safety practitioners have generally neglected the critical issue of skill transfer to different aquatic environments. Parents and teachers may falsely assume that if their child can swim in a pool they are "drown-proof," and likewise an increase in confidence by pool-trained swimmers may lead them to undertake more dangerous behaviors in the open water. On the contrary, according to the organization "Safe Kids Worldwide," the assumption that *a child that is able to swim in a pool will be safe in open water* may be one factor contributing to global drowning statistics (Mackay et al., 2018). Di Paola (2019) comments that: "Many swimming and lifesaving programs, although well-structured on paper, lack valid and reliable skills assessment and verification, which in turn might lead to inadequate skills acquisition and development, to a false sense of safety and to over confidence in the water that, as we all know, can be extremely dangerous." (p. 1).

Theoretical considerations for the design of water competency assessment

Motor skill performance is influenced by the task and environmental context (Newell, 1985), which may be problematic in the realm of water safety skills assessment: a multitude of factors differ between closed, controlled environments, and open water. Given the multitude of influential constraints that shape motor behavior, it can be very difficult to maintain fidelity in assessment environments (see section 4: practical considerations). Depending on the basic theoretical standpoint from which one views motor performance, one might make different conclusions on how skill should be assessed in open water surroundings. The two main theoretical frameworks that are common in motor behavior research are the ecological dynamics framework and information processing theory. In this next section, we will map out the conclusions that can be drawn when viewing the issue from each theoretical standpoint.

Information processing theories

Traditional information processing theories posit that programs stored within the central nervous system control muscle activation patterns for motor control. The organization of movement is seen as a top-down process driven by conscious processes and controlled in the cerebrum (Walsche, 1961). Skilled motor performance is viewed as an information processing activity guided by a general plan or program (Fitts, 1964). It may involve operations such as information translation, transmission, reduction, collation, and, most importantly, storage.

Information processing view on skill learning and assessment

The classical information processing model posits that information processing consists of three stages: stimulus identification, response selection, and response programming (Schmidt et al., 2018). During motor planning, a response (i.e., movement) and its control parameters (e.g., amount of force used) are selected and programmed, after which the motor command or program is executed *via* the motor cortex. During skill learning, relationships between control parameters such as speed and force and its outcomes, such as distance travelled, are learned (Schmidt, 1975, 2003; Sherwood and Lee, 2003). When we practice a motor skill that is relevant for water safety, we hope that this prepares us to cope with future situations – which are likely novel, unexpected and non-trained. Practice under more variable conditions is expected to accrue a more robust set of programs from which to inter-or extrapolate, and should therefore enhance learning (Boyce et al., 2006). Moreover, adaptation to novel situations (e.g., attempting to swim in waves) has also been shown to benefit from variable practice (Schmidt et al., 2018).

In variable environmental conditions, individuals have to identify and react to multiple, changing stimuli and select among a multitude of possible response options, while also adapting the control parameters of movement execution. Stimulus identification and response selection both become more complex. *Performing* in a more variable environment will therefore increase information processing demands and the chance of less-than-optimal response selection (Czyż, 2021), while *practicing* under such conditions may improve the future likelihood of succeeding in novel situations.

Based on recent efforts in computational and cognitive neuroscience (Clark, 2013; Koster-Hale and Saxe, 2013), a collection of models termed the *predictive processing framework* focus on the brain's ability to predict the future (see Spratling, 2017 for an overview of theories within this framework): The framework posits that an internal model of the world, created on the basis of movements and past sensory experience, is used to predict future sensory input (Hawkins and Blakeslee, 2004; Körding and Wolpert, 2004; Friston, 2005; Spratling, 2010). Being able to predict the future is a considerable advantage to the human brain. Not only can we anticipate the sensory consequences of our own movements, but also the dynamics of objects and other agents in the world (Keller and Mrsic-Flogel, 2018). For instance, an ocean-experienced person may look at a photograph or video of an ocean wave and instantly predict what will happen next.

Internal models are learned – indeed, experience shapes the circuits required for generating predictions and computing prediction errors. Therefore, it is the interaction with the world that refines these connections to generate precise internal models. In the context of water competence, it is experience in different aquatic environments (be it ocean, beach or harbor), and interaction with natural elements such as rips, currents, rocks or murky water, that enable us to predict potential consequences, make safe decisions, and coordinate our movements appropriately. Sensory experience sculpts the connectivity between neurons in an activity-dependent manner, e.g., neurons that code similar responses become functionally linked into a network (Ko et al., 2011, 2013; Cossell et al., 2015; Keller and Mrsic-Flogel, 2018).

During learning of skills, errors invariantly lead to a deviation of the sensory input from the model-based prediction. These prediction-error signals are processed by the primary sensory areas of the cortex, updating the predictive model. Variability in the learning environment is therefore crucial to the development of a valid and broad predictive model – or in other words, errors may be necessary to learn the full range of what the consequences are possible in which environment: this speaks for a broad range of aquatic experience in a variety of environments. When assessing learning, only a situation with sensory consequences that provides the full complexity of a predictive model may accurately measure the adequateness or "fit" of the model and its level of advancement (Schmidt et al., 1987).

Working memory and decision-making

When learning motor skills, the learner tests hypotheses about how best to perform the skill (Magill, 1998). For this they use sensory feedback to assess the success of their actions (Bruner et al., 2017). This hypothesis-testing strategy generates a set of performance rules (declarative knowledge) that the learner may retrieve during practice and performance, until the movement has become automated and can be released from declarative control (Maxwell et al., 2003). Information that is manipulated during a motor task is held in working memory, a mental "workspace" with limited capacity (Baddeley and Hitch, 1974; Baddeley, 2012). Human working memory has a limited capacity: usually, a person may be able to store, process or manipulate 7 bits of information at the same time (Baddeley, 1994). This leads to interesting conflicts when a person has to complete several tasks, as is often the case in water safety emergencies. A drowning situation requires appropriate execution of movements (swimming, floating, treading water) alongside complex decision-making (e.g., swim to shore or save energy by assuming HELP (heat escape lessening posture)). When deciding on the correct behavior after an immersion, it is therefore important that cognitive capacities are available to evaluate the options and choose correctly. The more complex the environment and the more sources of information need to be considered for a decision, the higher the load on information processing resources (Logie, 2011). Making decisions in complex environments is therefore an overarching skill that changes in the face of a changing environment. Concurrent decision-making and cognitive secondary tasks have been shown to have a detrimental effect on motor performance (Poolton et al., 2006). Based on this viewpoint, we would therefore predict that performance of a motor task when assessed in open water would be lower compared to a pool environment.

During accidental immersion and other drowning incidents, panic and psychological stress are likely to occur. Similar to cold shock, panic leads to a cascade of physiological, cognitive, perceptual, emotional, and behavioral responses (Cameron et al., 1987; Murray, 2004), which may hamper motor performance and decision making in an emergency (Page et al., 2016). To address issues related to information processing overload, teaching methods that avoid high cognitive load have been suggested by proponents of information processing theory. For example, the use of implicit learning methods has been suggested in other fields (Masters, 1992; Hardy et al., 1996). Implicit motor learning refers to the acquisition of a skill in a non-verbal manner, with little conscious awareness of what is learned (Masters, 1992; Masters et al., 2004). This can be achieved by errorless learning, (i.e,, avoiding or minimizing errors during practice), or analogy learning, (i.e., an analogy is presented instead of declarative rules or instructions about the movement, e.g., "float like a starfish"). Studies using analogy in teaching swimming have shown that analogy instruction is effective for promoting efficient movement patterns (Komar et al., 2014, 2019). Focusing externally (on the effects of movements) may be a further strategy that benefits motor learning in a similar way (for a review, see Wulf and Prinz, 2001). Benefits of implicit and external focus-inducing instructions indicate that these may be powerful and cheap solutions to address the problem of information processing overload, however only two studies have used these approaches in water-related skills (Komar et al., 2014, 2019).

Ecological dynamics theory

In contrast to information processing theories, the role of environment is central when one considers human behavior from an ecological dynamics theoretical perspective. How the environment is perceived in terms of opportunities to move, i.e., *affordances*, is a key idea from the ecological psychologist James Gibson. Gibson (1979) proposed that humans perceive objects, surfaces, or events by what they offer, invite, or demand in terms of action opportunities. Aquatic environment features such as waves and currents afford different actions for different people, due to, among other constraints, their distinct physical properties, such as their buoyancy (see Fajen et al., 2008; for key features of affordances discussed in the context of sport). According to Gibson (1979) perceiving the environment in terms of affordances renders dispensable those cognitive processes described above (Section 3.1) that transform action-independent perceptions into action-oriented perceptions. That is, in the process of direct perception, there is no integration and combination of cues involved.

Brunswik (1956) proposed the term *representative design* to advocate the study of psychological processes at the level of organism–environment relations. It means that perceptual variables should be sampled from the organism's typical environment so as to be representative of the environmental stimuli from which they have been adapted, and to which behavior is intended to be generalized. The pedagogical principle of representative design ensures that the information-movement coupling of the structured practice environment is relevant and representative of the performance context (Pinder et al., 2011). What this means is that relevant information sources and affordances of the 'to-be-learnt' performance context should be present in a practice task (Button et al., 2020b). Ideally, such a practice task would not need to be a simulation of the real world, but rather a "sampling" of stimuli and affordances from the real context.

The importance of representative learning design may have particular significance when we consider the assessment of water safety skills. Guignard et al. (2020) suggest low skill transfer might be expected when people learn aquatic skills in a swimming pool versus in outdoor aquatic environments. To design representative performance (i.e., assessment) environments, practitioners should consider the following factors carefully. First, what are the interacting constraints on movement behaviors and how are they represented in the environment (i.e., action fidelity/realism). Second, it is crucial to adequately sample informational variables from the specific performance environments (i.e., relevant affordances) and thereby preserve the functional coupling between perception and action processes. Finally, practitioners should ensure that (i) the degree of success of a performer's actions is controlled for, and compared between contexts (supporting transfer of skill and learning), and (ii) performers are able to achieve specific goals by basing actions (movement responses, decision making) on comparable information to that existing in the performance environment (Pinder et al., 2011).

In summary, both the information processing and ecological dynamics theories argue that practice in variable settings may lead to the development of more adaptable movement patterns that are better equipped to negotiate unpredictable demands (Reid et al., 2007). With regards to skills assessment, the ability to adapt one's movement solutions to changing environmental demands is best assessed in situations that pose such demands.

Practical considerations

In the following, we aim to provide some "food for thought" on the practical realization of water safety skills assessment. Although the focus is on assessment, most of these considerations may equally apply to the design of learning opportunities. The limited number of studies that have compared aquatic skills assessment between different environments forces us to rely on studies from different fields, theoretical considerations and preliminary data. In this light, we decided to include findings from two pilot studies, in the interest of driving future research efforts. Our priority was to explore potential difficulties associated with skills assessment in open water. Presumably, the paucity of research in this field may be related to worries about safety, limitations in available safety personnel and equipment, and access to safe outdoor environments. Case study 1 is a first attempt to determine whether water skill assessments in open water (1) are feasible and can be safely conducted, and (2) can lead to outcomes that are comparable to assessments in swimming pools. A second priority was to assess whether the use of an indoor flume (i.e., a pool through which a water current can be channeled at adjustable speed) could be an intermediate option for assessment of cardiorespiratory and physiological demands, as well as skill, during aquatic activities (specifically in this case, rescue). Since many physiological variables need to be assessed *via* advanced technological tools, it is – not least financially – near impossible to conduct such assessments in open water. If movement patterns (and, in future studies, physiological demands) could be replicated adequately in a controlled, indoor flume, this may open up avenues of skills assessment for the future (Pease, 1999). As such, case study 2 tells the story of a first attempt to simulate the full range of lifeguards' movement patterns in a flume.

Case study 1: Assessing children's aquatic skills in open water and closed environments

Background

Button et al. (2020a) have recently explored different methods and environments to undertake a range of water safety assessments for young children. In this case study, we draw upon some of that data (which was collected in an indoor pool), and compare it with more recent data (collected in open water, van Duijn et al., 2021a). This will enable us to compare the outcomes of the same water safety skill assessment battery between the two environments.

Method

The indoor swimming pool that was used for assessments by Button et al. (2020a) was an 8 × 25 m rectangle, with a shallow (1.2 m) and deep end (2.5 m) joined by a continuous sloping floor. The pool had an access ladder in each corner and a support rail along each wall. For all testing sessions, the water temperature was set at 25°C. The open water environments were two similar beach reserves located in a harbor (see Figure 2). For the open water assessments, weather conditions were closely monitored and testing only proceeded in relatively settled conditions (i.e., ambient temperature + 13°C, wind <30 km/h). The swimming pool was booked for the purpose of testing and therefore not accessible by the general public but the open water environments were publicly accessible.

Two different groups of school aged children (5–13 years old) undertook four fundamental water safety skills assessments either in the swimming pool or harbor environments described above. There were 98 pool-tested children (44 female and 54 male) and 58 harbor-tested children (20 female, 38 male). The samples did not include complete novices (i.e., non-swimmers). The four tasks assessed were: a) floating and treading water (1 min of floating on the back as in Figure 3, followed by up to 4 min of treading water), b) completing an obstacle course, c) an underwater swim (surface dive and retrieve a submerged object 2–5 meters away) and, d) a continuous swim (swim using any stroke continuously for either up to 5 min or 100 m). All assessments (both pool and open water) were closely supervised by lifeguards and undertaken by experienced observers. Each task was visually assessed and graded on a 4-point scale.

Results

There were no notable or consistent differences in competency between pool and harbor environments. Independent sample Mann–Whitney U tests confirmed that there were no significant differences ($p > 0.05$) between competency scores in any of the four tasks. Regardless of the environment in which assessment occurred, older children (9–12 years) were more competent than younger children (5–8 years). One might have predicted the younger children (i.e., lower skilled) would be more nervous than the older children about being tested outdoors and hence their competency assessments would be reduced. However, the data did not support this prediction as younger children did not appear to perform worse in the open water tests than in the pool. The four skills seemed equally challenging for the children although the younger children showed a tendency toward lower scores in the floating/treading water and continuous swim tasks (Figure 4).

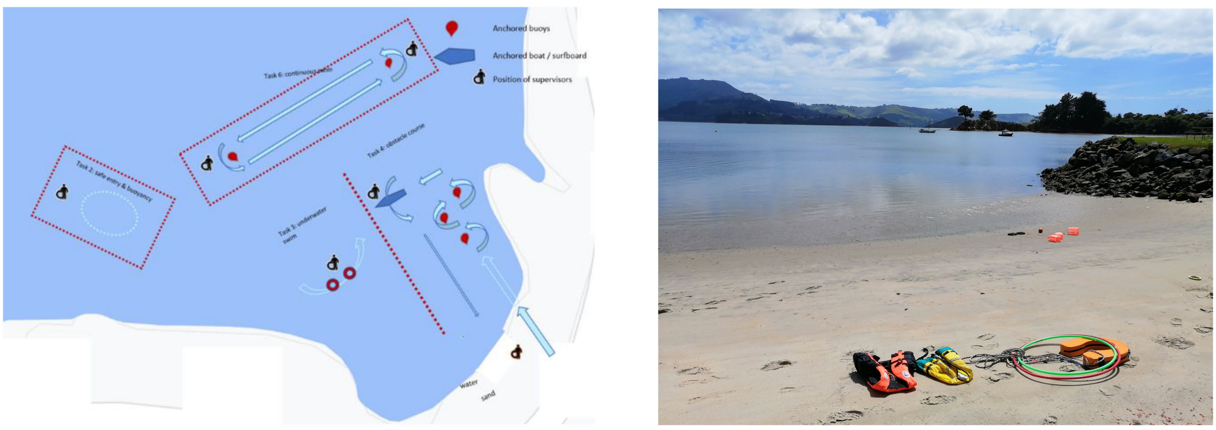

FIGURE 2
Experimental set-up for the outdoor testing sessions of the study. Left: Plan of the setup. Right: Overview of the beach testing location.

FIGURE 3
Impressions from the data collection: indoor testing in a pool (left) vs. outdoor testing in a harbor (right).

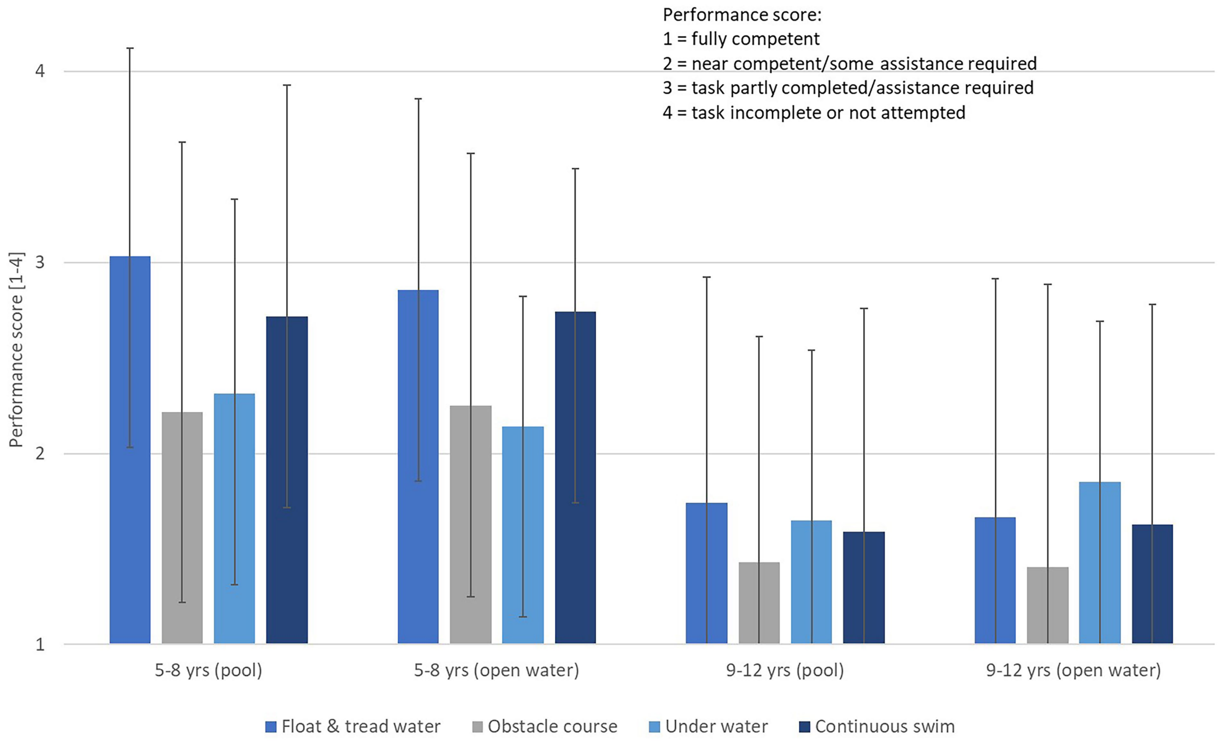

FIGURE 4
Comparison of water safety competency when children of different ages were assessed in a pool or in open water.

Discussion

An important component of water safety education is getting children to identify risks and how to manage them. This is very difficult to do in a swimming pool where the risks are different to outdoor aquatic environments. The fact that the open water assessments did not proffer different results from the study of Button et al. (2020a) imply that assessments of water competency may be successfully undertaken outside of a swimming pool. However, there were several challenges to overcome in terms of conducting skill assessments in a public harbor including ensuring adequate supervision, monitoring for boats and other water-users, and late cancelation of sessions due to poor weather. Assuming

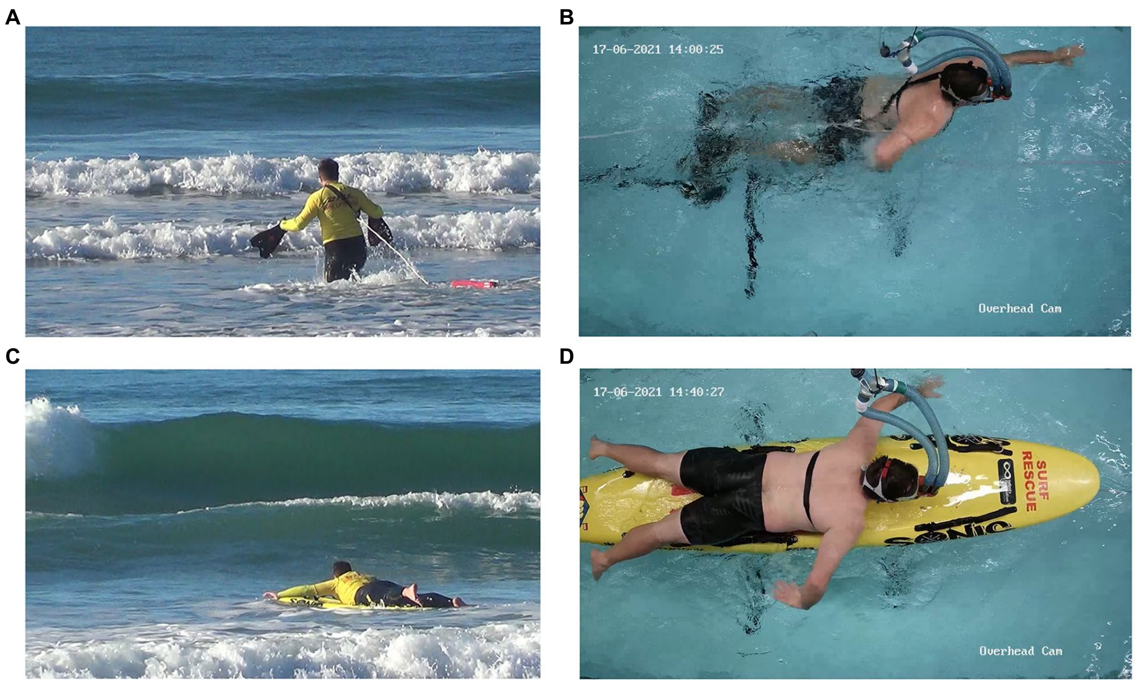

FIGURE 5
A lifeguard performing a tube rescue in open ocean **(A)**, a tube rescue in and controlled flume conditions **(B)**, a board rescue in open ocean **(C)**, and a board rescue in controlled flume conditions **(D)**.

that such risks are managed appropriately it is possible to test water safety competencies in open water. Although younger children tended to perform less competently than older children (as would be expected), there was no strong evidence to suggest this difference is exacerbated when assessments take place in open water.

Case study 2: Movement patterns used by surf life guards in open water and closed (laboratory simulation) rescues

Introduction

Typically, assessment of lifeguards' swimming abilities has been conducted in closed, pool environments (Daniel and Klauck, 1992; Prieto Saborit et al., 2010; Salvador et al., 2014). However, reducing environmental complexity has been shown to alter the interaction between lifeguard and patient (or manikin, Avramidis et al., 2009), as well as gaze behavior and likely information processing (Seth and Edelman, 2004). Therefore, the external validity of pool-based lifeguard assessment may be questioned (Davids et al., 2006; Tipton et al., 2008; Holleman et al., 2020). As a compromise, flume environments allow to simulate some factors of an outdoor environment (e.g., current, waves, multitasking, longer distances without pause), while controlling the elements that would hamper valid and reliable data collection. Although flume testing has also been shown to alter swim technique when compared to indoor pools (Pease, 1999; Wilson et al., 2011; Espinosa et al., 2015; Guignard et al., 2017), a direct comparison with open water swimming has not yet been performed to our knowledge.

Method

This pilot study was conducted with five male experienced lifeguards (age: 16–51 years, experience 2–22 years). Two simulated rescues were performed by the lifeguards in a beach environment (open ocean, waves up to 3 ft) – one rescue by rescue board, and one by using a rescue tube and fins. Participants were asked to retrieve a manikin that was positioned in the water 100 m from shore as fast as possible. The type, order and duration of aquatic locomotion movements during each field test were subsequently described by an expert, and replicated step-by step in an indoor flume (see Figure 5 for a direct juxtaposition of the two environments): i.e., participants performed running, bounding, diving, swimming and paddling movements while their own video recording from their beach trial was played back to them. The speed of water flow in the flume was matched to the average speeds at which participants were moving during the beach trial. Based on expert categorizations, the type and duration of each movement pattern during each of the four tests was analyzed exploratively.

Results

During beach trials, participants employed a wide range of movement patterns (see Figures 6, 7). The relative time that participants spent in each pattern showed likewise large variations

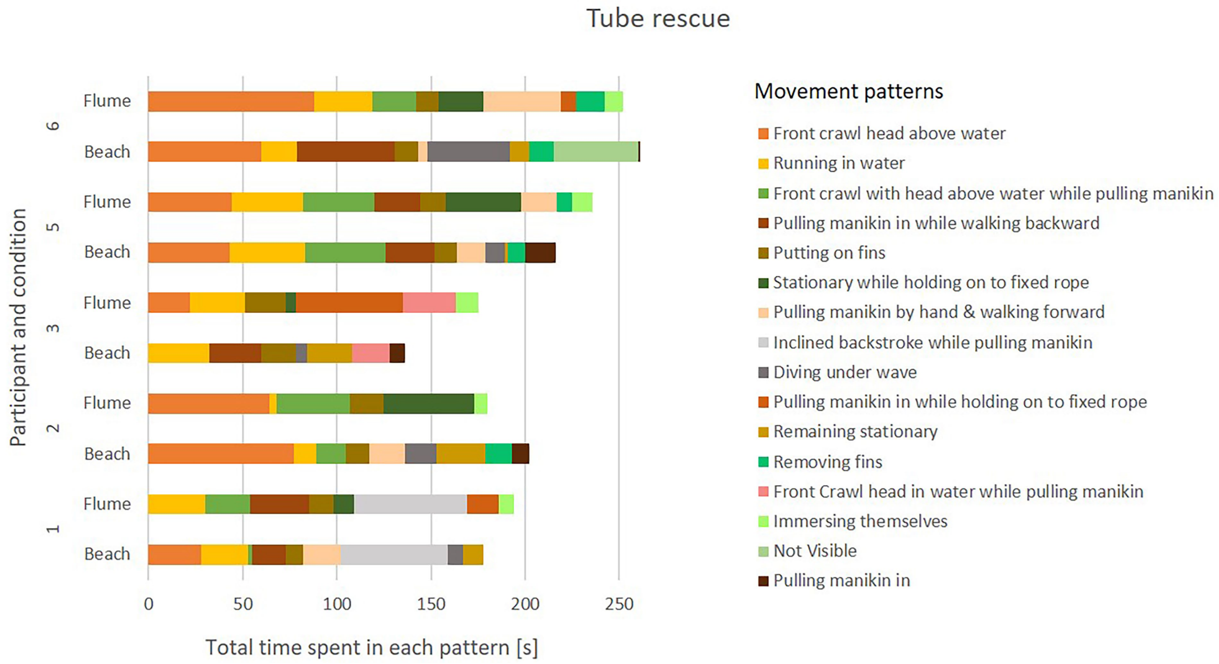

FIGURE 6
Movement patterns employed during tube rescue in ocean vs. flume conditions.

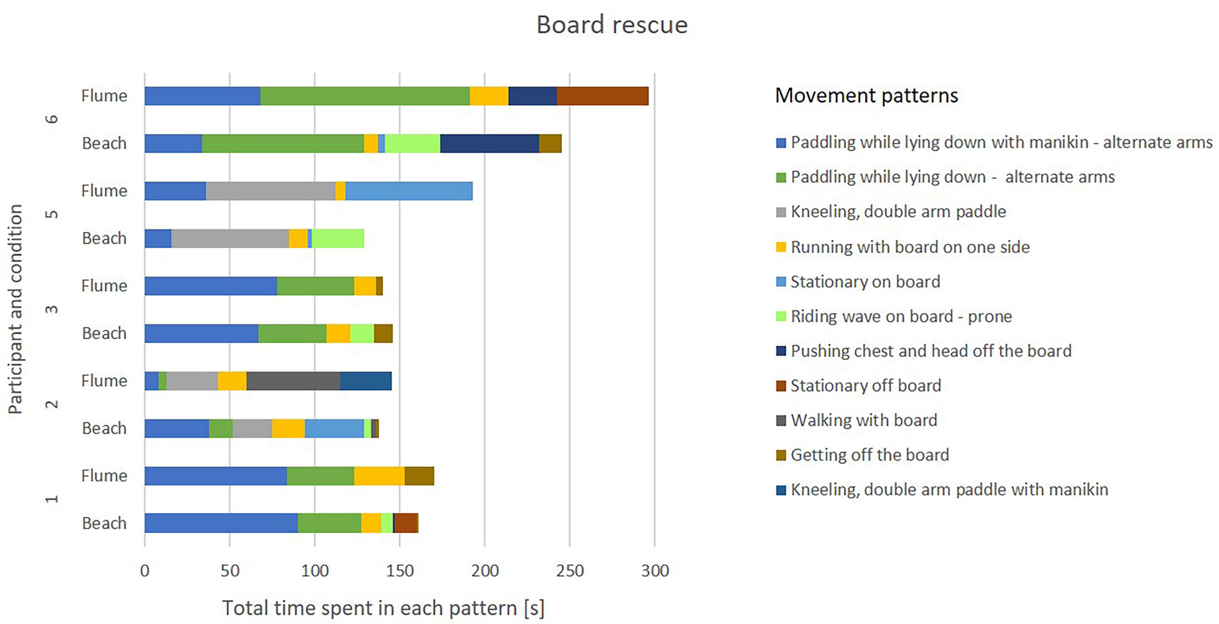

FIGURE 7
Movement patterns employed during board rescue in ocean vs. flume conditions. Note: The colors do not indicate the same patterns as in Figure 6.

between participants. Within-participant comparisons of beach vs. flume movements suggest that the replication of movement patterns in the flume may have been overall successful, however, modifications due to the environment (water flow and pool depth) are clearly visible in the exhibited movement patterns. As an example, the pattern "diving under wave" was replaced by "immersing themselves," a slightly adapted movement that mimics the former.

Discussion

Based on qualitative comparison of the movements, the replication of movement patterns in the flume seems feasible. However, it is likely that the flume replication may not have captured the intensity of the original movement, as participants reported finding it less taxing in the flume. Due to equipment limitations, it was not possible to fully replicate the "push back" resulting from waves, as well as some aspects of the original movements (e.g., walking in shallow water, overcoming breaking waves while fitting swim fins) and decision-making stimuli (e.g., timing, positioning, and patient status). Important aspects pertaining to the learner-environment interaction (perception-action coupling) may therefore have been missed in the simulation. If simulation fidelity is necessary for successful skill transfer to the real world, as suggested for example by Taber (2014), cognitive and psychological demands on the rescuer may also have to be simulated correctly.

Conclusion

This study was first attempt to replicate rescue movement patterns in a controlled flume setting. While flume-based simulations may allow correct replication of movement patterns, they are unlikely to represent the full range of demands (physical, cognitive, mechanical) presented when performing rescues in open water.

Reflections on the type of competencies required to be safe in the water

As case study 2 shows, navigating open water environments may require perceptual and motor skills that are difficult to simulate in a controlled aquatic environment. It is clear that the characteristics of the environment dictate which skills are necessary to safely move around in it. When assessing skill, the relative importance that is attributed to different motor competencies should, in our view, depend on the environment in which the skill is predominantly applied. As an example, it is clear that immersion in cold water poses a direct threat to survival - either *via* the initial cold shock response involving gasping, hyperventilation, hypocapnia, tachycardia and hypertension, or subsequent hypothermia (Datta and Tipton, 2006). Immersion in cold water also affects people's movements, rendering them stiff and inefficient. Thus, in a situation where a person falls into cold water, they need to have the knowledge that cold shock will cause them to gasp, have a high heart rate, and feel dizzy – but that it will subside after 2–3 min (Barwood et al., 2016). Such a situation would also require the person to be able to float first (i.e., for the time it takes for cold shock effects to dissipate) and then coordinate movement effectively to get out of the cold water quickly. In comparison, immersion in warm, but moving water might require a person to start swimming toward safety immediately, and would not require knowledge of cold shock. As a second example, many drownings or hospitalizations due to water-related injury have implicated clothing as an influential factor. Clothing likely impacts movement in the water *via* entrapment and by increasing the weight of the casualty (Keatinge, 1969), and thus also increases energetic, cardiorespiratory and cognitive demands on the swimmer (Choi et al., 2000; Stallman et al., 2011; Moran, 2014). Extending skills assessment to clothed swimming might be necessary to predict how well a person is able to cope in case of a realistic open water immersion incident. Whether a newly learned motor skill is transferred to performance in cold water and while wearing clothing has rarely been investigated (Schnitzler et al., 2017).

Another important component that defines the ability to move safely in aquatic environments is awareness of risks. Pitman et al. (2021) asked beachgoers to identify rip currents in photographs and *in situ* at a beach. They found that only 22% of respondents were able to identify the *in-situ* rip current, and of the respondents who correctly identified a rip current in photographs, 34% made correct *in situ* rip identifications. Furthermore, decision-making in aquatic environments heavily relies on accurate estimation of distance as well as one's own motor and fitness and energetic capacities (Baird and Burkhart, 2000; Ducharme and Lounsbury, 2007). This highlights that perceptual performance may differ depending on the environment: photographs may not be the best means of teaching, nor of assessing the skill of identifying risk factors of the environment (e.g., Proffitt, 2006). The use of immersive and realistic simulations may be an avenue to explore in this respect (Baird and Burkhart, 2000; Ducharme and Lounsbury, 2007). Different culturally and socially developed habits, traditions and practices in relation to interaction with water are an important factor that needs to be pointed out here. For example, in bicultural New Zealand, a traditional Māori practice is food gathering in the ocean, through which a deep spiritual connection with nature is reached for, while recreational swimming in swimming pools is not very common. The colonial *Pakeha* population (European New Zealanders), by contrast, spend more time relaxing on the beach, surfing, or swimming for fitness in indoor pools (Phillips, 2020; Wheaton et al., 2020). With regards to assessment, this means that cultural factors should be considered when the ideal skillset for a person, in a given environment, is defined and assessed.

In summary, assessment of water competencies should differ depending on the physical and cultural environment under consideration, since the nature of the skills that are required to be safe depend on this environment. Due to the wide variety of open water locations, and thus of environmental constraints, assessment of water competencies needs to be situation-specific and tailored to the goal competencies that are deemed relevant.

Reflections on optimal assessment tools in different environments

As we reflect on a wide range of complex issues, we must first acknowledge that perhaps the most important factor for assessing water safety competency that we have not discussed is the assessor themselves. They must be familiar with the appropriate behaviors to be demonstrated in each aquatic environment. For this reason, it is vital that experienced and trained practitioners undertake water safety assessments whatever the location. However, as we have explained at length in this article, the environment also dictates what is feasible and effective in regards to assessment.

In case study 1, the open water environments impacted how assessments were undertaken. It was discovered that using fixed buoys as reference points was problematic, as the changing tides led to ever-changing water depth. Fluctuating water conditions introduces various difficulties for testing such as increasing anxiety for those being assessed and potential exposing objects (e.g., rocks) that may have been covered in sand. As another example, while video recording may be applicable on a steep beach where it is easy to achieve an overview in a single frame, a river may not afford this way of assessing. Vice versa, monitoring testees on a boat may be more suitable in a river compared to a beach-break situation.

Measurement of water safety skills often involves assessing the maximal distance or time that a person can swim. Measurement tools to achieve this in open water could include a floating rope, buoys (useful in still water), a range finder (especially useful in waves, see case study 2) or a video recording with fixed points on land (e.g., in a river). The environment sometimes dictates specific clothing, which may in turn affect movement characteristics. A pertinent example is the wearing of wetsuits in cold water, which, although arguably necessary, changes the buoyancy of the learner, and their performance at certain tasks. Open water assessments are also impacted by waves and wind, which are hard to control and likely reduce the reliability of a testing scenario. Choosing a sheltered spot, though it reduces this risk, may alter a key constraint associated with the task, simplifying it and rendering it less externally valid. On the other hand, simulating elements of unpredictability that are common for open water contexts may be possible in pool settings: Perhaps using technologies such as wave machines, lazy rivers, and cold-water cannons in a pool may allow for a closer representation of open water features.

Assessment tools also need to include retention of skill over time and transfer of skills to more complex environments. One difficulty with delayed retention tests are changes in air and water temperatures with the changing seasons: a retention test at the end of summer will likely involve cold water (effectively rendering it a transfer test, see effects of cold water on motor skills described above). A transfer test is an ideal opportunity to test whether a child can cope with a novel scenario – ideally, it would assess whether the individual skills are being recalled, linked and executed in a realistic, outdoor setting. An example could be a simulated self-rescue which might involve surfacing, floating, treading water, navigating around objects and returning to shore. By assessing skill over a longer time scale, it would further be possible to confirm whether general transfer and learning transfer is improved (i.e., learn to learn, see Oppici and Panchuk, 2022). Additional to physical skills such as swimming, it may also be relevant to assess decision-making capability, which is even more tightly related to information that is available in the environment, and benefits from outdoor assessment. For example, a task "swim as far out as you can and come back" includes distance estimation, decision-making and estimation of maximal action capabilities. Such tasks can easily be adapted to open water, including waves and currents to enable assessment of the robustness of such skills to variable environments.

Clearly, assessment tools (i.e., skills and knowledge tests, or observational grading scales) also need to be tailored to the expected variability in skill level: a fine-grained scale that allows to discern small individual differences may be necessary in one situation, whereas in another the main goal might be to determine who can be unsupervised, and a rougher grading scale or single criterion may be used. This points toward the use of complex, multifactorial tests of movement and decision-making in a realistic environment to capture the person's ability to cope in such situations. Transfer of each individual skill to a combined skill has rarely been tested in a water safety context (for an exception, see Button et al., 2022).

Summary: Benefits and caveats of assessment in naturalistic environments

As we have previously highlighted, the assessment and learning of skills are closely intertwined. The variability and unpredictability of naturalistic environments would require self-organization by the learner. Additionally, this type of environment may favor perception-action coupling in a sense of a representative testing design, as learners will engage with the real context of performance. Naturalistic environments can help us educate to intention, i.e., to engage in task-goal oriented activity, involving searching strategy and decision-making especially in estimating risky places to swim vs. safe places to enter in the water and swim. For instance, being aware of low/high tide times would change the intention of learners, as a beach could be safe because sandy and flat at low tide, whereas this same beach could be dangerous because rocky with steep slopes at high tide. Thus, naturalistic environments would require that a learner explores their various possibilities of action (and consequently make decisions), such as where to enter and exit; in comparison to a swimming pool where safe access is more obvious (i.e., ladder vs. edge of the pool). Furthermore, naturalistic environments help to educate to attention, i.e., to attune to relevant information for action. For example, instead of learning what a risky situation is from photographs and simulation in a swimming pool (which arguably represent the structural properties of an environment), learners are invited to perceive functional properties of the environment. This process supports the perception of affordances (opportunities for action) relative to the learner's own action capabilities.

More broadly, the naturalistic environment requires the learners to select, within a rich landscape of affordances, the action that best fits their action capabilities and intention. For instance, entering clear water (i.e., ground is visible) does not afford the same actions as does blurry water, because potential seaweed and rocks may change what types of locomotion are best suited. When the ground is visible, a learner might jump into the water whereas when it is not, they might use water shoes or walk smoothly into the water. Hence, whether the aim for the practitioner is learning or assessment of water safety skills, there is potentially much to be gained from utilizing representative environments.

As summarized in Table 1, the numerous benefits of assessing in naturalistic environment are accompanied by caveats. For example, difficulties arise in maintaining high reliability, as practitioners must control the variability and unpredictability of naturalistic environments. Replicability of a testing scenario is also important to allow comparisons between different kinds of naturalistic environment. A sharper focus on skill transfer (rather than skill reproduction) also seems necessary which may require assessment in multiple open water environments. We recommend that practitioners should carefully weigh up such benefits and caveats in designing water safety assessments in naturalistic environments.

Conclusion and future research

In this article we have argued that water safety skill assessments must be carefully designed to reflect the range of competencies that may be required in naturalistic environments. Aquatic competency involves much more than just swimming. Assessment batteries that separate specific testable skills seem necessary to reflect the range of behaviors that may be required to remain safe in and around water. Contemporary motor learning theories support the inclusion of task and environmental variability to show how robust the performer is to variations that are common in natural aquatic environments. However, future research is needed to:

a. Determine the effects of environment on the production of fundamental aquatic skills.
b. To investigate the transfer of skills from the controlled environments to real-life open water situations.
c. To assess the reliability and validity of aquatic skills assessment tools with regards to predicting open water competence, risk of drowning or injury.
d. To find out whether, or to what extent, simulation of psychological and physiological demands is feasible in controlled lab-environments.

We have provided initial evidence that assessment in open water is possible, especially if the outdoor environment can be managed appropriately. There are important caveats that practitioners must carefully weigh up when designing assessment activities however, in our opinion the many benefits to be gained from testing in naturalistic environments outweigh such concerns.

TABLE 1 Benefits and caveats of skills assessment in open water.

Aspect	Benefits of assessing in open water	Caveats of assessing in open water
Quality of assessment	High external validity	Need careful designing to enable high construct validity – often, skills are not clearly separable Replicability requires precise definition of all parameters
Assessment of competencies beyond motor skills	Accurate simulation of information processing load Adaptability of the skill can be assessed accurately Perception-action coupling is similar to what is required in open water Accurate representation of relevant information for decision-making assessment	Difficulty to separate motor skills from other aspects
Individual differences	Individual differences in open water skill may be adequately shown	High variability makes consistent testing difficult. Need for a fine-grained assessment scale and for splitting skills into sub-components
Skill transfer	Best way to assess transfer of skill into relevant environment	Difficult to separate skill learning from transfer
Cultural relevance	Possibility to include wide range of practices and forms of interaction with the environment	
Safety	Possible to conduct safely in appropriate environment	Requirements at schools often extreme: need for high ratio of supervisors: learners Requirement to choose predictable environment reduces value of open water testing
Time efficiency	–	Requires more time to plan and run

Author contributions

TD contributed to study concept and design (case study 1 and case study 2), acquisition of subjects (case study 1), data collection (case study 1 and case study 2), and preparation of the manuscript. CB contributed to study concept and design (case study 1 and case study 2), acquisition of subjects (case study 1), data collection (case study 1 and case study 2), analysis and interpretation of data (case study 1), and preparation of the manuscript. KC contributed to study concept and design (case study 2), acquisition of subjects (case study 2), data collection (case study 1 and case study 2), analysis and interpretation of data (case study 2). LS contributed to interpretation of data and preparation of the manuscript. All authors significantly contributed to the research process. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY
Gillian Weir,
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João Paulo Morais Ferreira,
Superior Institute of Engineering of Coimbra (ISEC), Portugal
Thurmon E. Lockhart,
Arizona State University, United States
Patrick Mai,
German Sport University Cologne, Germany

*CORRESPONDENCE
Abhishek Sharma,
as711@uw.edu

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Complexity of locomotion activities in an outside-of-the-lab wearable motion capture dataset

Abhishek Sharma[1]* and Eric Rombokas[1,2]

[1]Department of Mechanical Engineering, University of Washington, Seattle, WA, United States,
[2]Department of Electrical Engineering, University of Washington, Seattle, WA, United States

Gait complexity is widely used to understand risk factors for injury, rehabilitation, the performance of assistive devices, and other matters of clinical interest. We analyze the complexity of out-of-the-lab locomotion activities *via* measures that have previously been used in gait analysis literature, as well as measures from other domains of data analysis. We categorize these broadly as quantifying either the intrinsic dimensionality, the variability, or the regularity, periodicity, or self-similarity of the data from a nonlinear dynamical systems perspective. We perform this analysis on a novel full-body motion capture dataset collected in out-of-the-lab conditions for a variety of indoor environments. This is a unique dataset with a large amount (over 24 h total) of data from participants behaving without low-level instructions in out-of-the-lab indoor environments. We show that reasonable complexity measures can yield surprising, and even profoundly contradictory, results. We suggest that future complexity analysis can use these guidelines to be more specific and intentional about what aspect of complexity a quantitative measure expresses. This will become more important as wearable motion capture technology increasingly allows for comparison of ecologically relevant behavior with lab-based measurements.

KEYWORDS

complexity, wearable motion capture, out-of-the-lab datasets, gait analysis, real-world scenario, on-field movement analysis, human locomotion

1 Introduction

Measurement of the complexity of motor output (Decker et al., 2010; Morrison and Newell, 2015) is a common and essential component of gait analysis. It can be used for basic science, providing a window into how the brain generates movement Ting and McKay (2007), performs sensation, and how neural control interacts with biomechanics (Duysens et al., 2013). It can also be used for clinical gait analysis, with real implications for prescription of interventions and functional classification e.g., (Steele et al., 2015a). For example, a decrease in motor output complexity might indicate a reduced ability to adapt to stresses (Peng et al., 1993; Amaral et al., 1998; Goldberger et al., 2002). According to this reasoning, decreased complexity could indicate a reduced capacity for rejection of variability Goldberger et al. (2002), or a deterioration of the complex human rhythms of movement associated with healthy function Decker et al. (2010). It might also serve as a

TABLE 1 Activities and subject details.

Activities	# Subjects	Age (yrs)	Height (cm)
Forward walking	9 females; 11 males	26.2 ± 2.7	174 ± 10.9
Backward walking	4 females; 5 males	21.5 ± 2.4	173.4 ± 6.9
Sidestepping	4 females; 5 males	21.8 ± 2.2	172.8 ± 6.8
Classrooms and Atrium	12 females; 11 males	22.8 ± 2.7	171.2 ± 9.7

tool to examine how well the current techniques used in control of assistive devices approximate the natural human gait. For example, it is well known that human gait exhibits variability (one measure of complexity) across strides due to several factors like environment or fatigue, while the control of assistive devices is often rigid and deterministic. Since different activities exhibit varying degrees of complexity, it may be that if a deterministic control technique works for one activity with low variability, it will not translate well to different, highly variable, activity. Thus, examining the variability (and more broadly, the complexity) of different activities, is needed.

In the past, gait datasets have been largely confined to in-the-lab environments. Most available gait data has been restricted to uncluttered level ground ambulation or walking on a treadmill. As a result, much of the analyses and conclusions about human gait are drawn from a limited context. For example, there are no previous studies that compare commonly recorded gait activities like forward walking in a straight line to daily unconstrained walking in public places in terms of their complexity. However, recent developments in wearable sensors have driven increased interest in measuring human movement under a more diverse set of activities and situations. This makes it possible to analyze and compare these activities with the most commonly analyzed activity: flat ground walking in a straight line.

It is actually not trivial to quantitatively measure and define the relative complexity of different activities (Morrison and Newell, 2015). From our natural experience of life, we understand that avoiding obstacles, navigating challenging terrain, or dealing with uncertainty in the environment should result in more complex movement. We also intuit that movement outside of a gait lab, in the presence of other people and a changing environment, should result in more complex movement. But what, precisely and quantitatively, does that mean? There are several reasonable quantitative measures of complexity that actually are measuring different aspects of the data, and *can be contradictory*.

In this manuscript, we attempt to define reasonable boundaries for these questions, and demonstrate some experiments and measurements that begin to answer them. Our goal is to contribute to a standard practice of gait complexity analysis, and especially comparison of different activities, as movement studies increasingly take place in more natural, unconstrained contexts. We present a multi-subject (See Table 1) full body kinematics dataset that captures diverse activities like forward walking, backward walking, side stepping, avoiding obstacles by stepping over them, navigating around obstacles in structured and controlled environments as well as unstructured and uncontrolled natural environments, and stair ascent and descent. We qualitatively and quantitatively compare these activities to straight-line forward walking.

First, we provide background and context for complexity analysis in Section 2. We also present the potential contradictions in different complexity measures using a toy example. In Methods (Section 3), we describe the experiment, data analysis details, and quantitative outcome calculation methods. In Results and Discussion (Section 4) we present comparisons of the relative complexity of the different activities, and consider the importance of these outcomes, especially when different notions of complexity result in apparent differences. Finally, we discuss some limitations of our analysis.

2 Background: Complexity analysis

Previous analyses of complexity may be generally categorized as being inspired by three notions (Decker et al., 2010; Morrison and Newell, 2015): 1) dimensionality, 2) variability, and 3) nonlinear dynamics. Here we use measures from each of these. As we describe in the Results and Discussion, there can be important differences in the apparent complexity of gait depending on the specific measures being used.

2.1 Complexity in terms of dimensionality

This approach assumes that the greater the number of dimensions (degrees of freedom) required to describe the data, the greater the complexity of the data (Morrison and Newell, 2015). A common method used to capture dimensionality of the data is Principal Component Analysis (PCA). Dimensionality is defined as the number of principal components required to capture a certain level of variance in the data. The greater number of PCs required to explain the desired level of variance in the data, the greater the complexity of the data. There are a variety of other matrix factorization algorithms are used to identify underlying regularities or synergies in movement data (Steele et al., 2015b). As we have shown in other work, there are other advantageous nonlinear methods of identifying the underlying dimensionality (Portnova-Fahreeva et al., 2020; Boe et al., 2021). However, the most straightfoward method commonly used in the current gait literature is PCA (Morrison and Newell, 2015), so we will constrain ourselves to that measure for this analysis.

2.2 Complexity in terms of variability

An alternative way to measure complexity is to assess the amount of deviation in a signal. For example, the Standard Deviation (SD) or Coefficient of Variation are common measures that use this approach (Morrison and Newell, 2015). This allows the complexity of even very low-dimensional data to be quantified meaningfully. For multi-variate data the determinant of the covariance matrix, also known as Generalized Variance (Wilks, 1932), can be used a variance measure. Another measure of variability (GaitSD) has been proposed in (Sangeux et al., 2016), to measure the variability of gait waveforms across strides. Larger variability implies greater complexity under these definitions.

2.3 Complexity in terms of non-linear dynamics

Tools from non-linear dynamical system theory have been used to measure the regularity and periodicity of gait signals across time (Decker et al., 2010). describes two kinds of analyses: State space examination and self-similarity evaluation, used to assess gait complexity.

State-space examination is done using the Largest Lyapunov Exponent (LyE) and Correlation Dimension. The LyE measures the average exponential rate of separation of neighboring trajectories of the attractor, while Correlation Dimension is a measure of the fractal dimension of the attractor. A positive LyE indicates aperiodic signals while a negative or zero LyE are associated with periodic signals. Random data are generally characterized by a large Correlation Dimension and LyE values while deterministic (periodic or chaotic) data exhibit smaller values.

Self-similarity evaluation is done to examine the presence of repeating patterns in the gait signal. Entropy based measures like approximate entropy (ApEn), sample entropy (SampEn), detrended fluctuation analysis (DFA) and multiscale entropy (MSE) are used to this end (Costa et al., 2005).

2.4 Contradictions in measures of complexity

These are all reasonable, but potentially contradictory, quantitative measures of complexity because they are measuring different characteristics of the data. We can understand this from the following 2D toy example in Figure 1 as follows: In the first row, we see two Gaussian data clouds which we can imagine as being generated by two different activities. Consider if we define variance of the data as the measure of complexity. We could reasonably use Generalized Variance for multi-dimensional data (Wilks, 1932), which is defined as the determinant of the covariance matrix (Σ). We would rank the red cloud to have greater complexity, because the red cloud implies people need to attain a broader range of distinct states with their body. On the other hand, if we use dimensionality as the measure of complexity, we would not be able to distinguish between the two activities, as both equally employ the 2 available degrees of freedom.

In the second row, we see that a dimensionality measure would rank the blue activity to be more complex, since the red activity seems to be generated by a single independent factor, while the generalized variance would rank both the activity clouds to be of similar complexity.

These examples highlight that we need to exercise caution when discussing complexity. Although it appears to be a concrete and quantitative concept, it is necessary to be more specific about what kind of complexity we are measuring. In the toy example, simple visualization of the data helps to provide an intuitive grounding, but as we analyze time series data from many sensors simultaneously, we cannot rely on intuition. In the remainder of this manuscript, we will demonstrate this concretely using five standard complexity measures.

3 Methods

3.1 Experiments and subjects

For each data collection session, the subject was briefed about the experiment and informed consent was obtained. All activities were approved by the Institutional Review Board at University of Washington. The entire dataset will be made available on a public repository (https://github.com/abs711/The-way-of-the-future) and more details about the data are presented in (Sharma et al., 2022) Subjects' joint kinematics were recorded using an Xsens Awinda full body motion capture system (*Xsens Technologies, Enschede, Netherlands*), consisting of 17 body-worn inertial measurement units placed at each segment of the limbs, as well as sternum, sacrum, shoulder scapula, and forehead. After a system specified n-pose calibration, the software provides joint kinematics in a 3D environment. All angles are in 1×3 Euler representation of the joint angle vector (x, y, z) in degrees, calculated using the Euler sequence ZXY using the International Society of Biomechanics standard joint angle coordinate system (Wu et al., 2002). Data were sampled at 60 Hz, from a total of 22 joints in 3 anatomical planes (sagittal, frontal, transverse) for each trial. The kinematics data were reprocessed

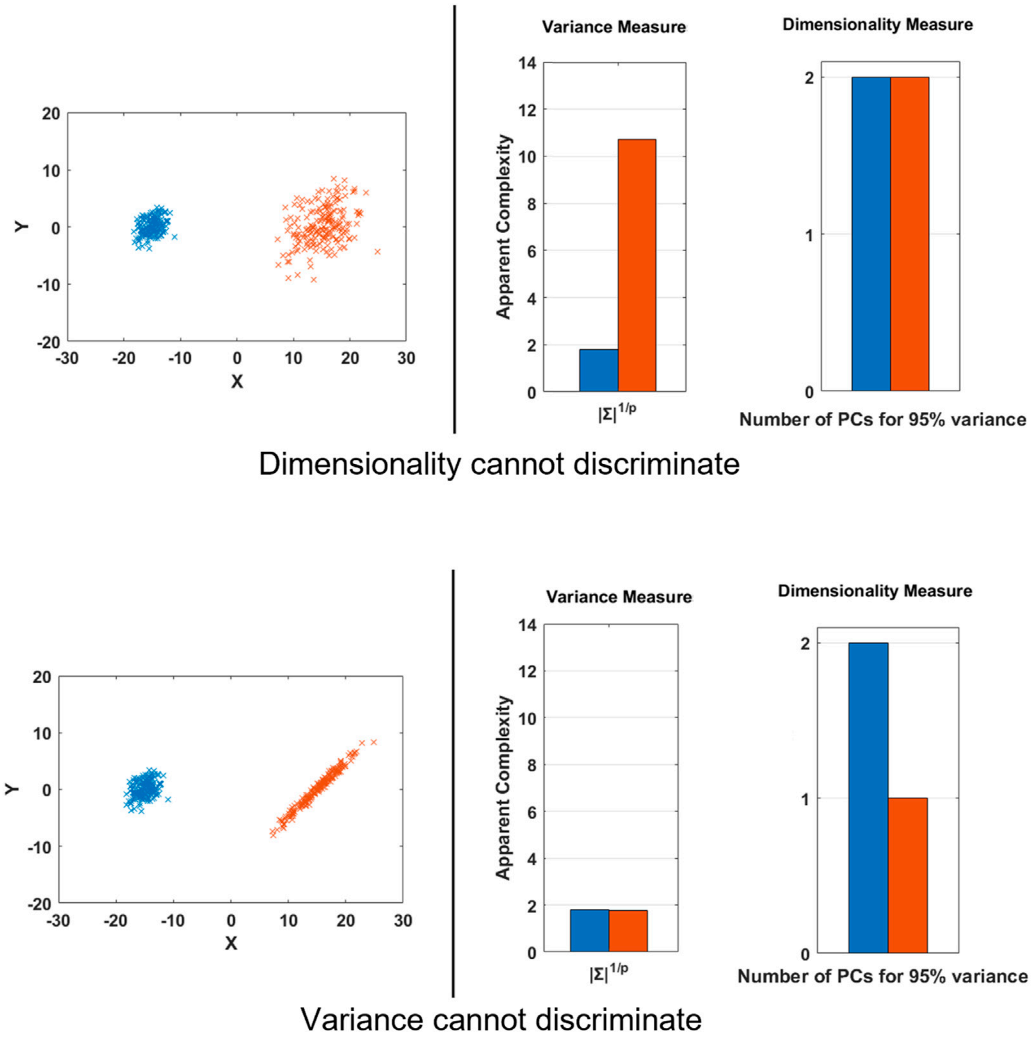

FIGURE 1
Toy Example to demonstrate some cases when different measures of complexity can fail to discriminate two distinct datasets and lead to contradictory outcomes. This example deals with only variance and dimensionality, but similar parallels exist for the other measures of complexity, such as stability from a nonlinear dynamics perspective.

using the 'HD' processing feature, provided by the manufacturer for offline use, to enhance quality and remove noise (Myn et al., 2015).

In this manuscript we limit the complexity analysis to kinematics data from only the lower limb joints: hip, knee and ankle from sagittal, transverse, and frontal planes for both the limbs. Thus, a total of 3 anatomical planes from 6 lower limb joints were used in our analysis i.e., 18 degrees of freedom.

Subjects ambulated in a variety of ways, including walking, sidestepping without crossing legs, navigating through obstacles, making turns, etc. as they deemed necessary in order to navigate the environment. Their speed was self-selected and their path around obstacles was not instructed. The movement was performed outside of a laboratory, in the corridors, indoor rooms and atrium of a building. The architecture for one of the classrooms and the atrium is shown in Figures 2, 3. The dataset was manually parsed into six activities for analysis. The activities that were parsed out for complexity analysis are: 1) **Forward walking** (straight line), 2) **Backward walking** (straight line), 3) **Left sidestepping**, 4) **Right sidestepping**, 5) **Navigating in classrooms**, and 6) **Navigating in an atrium**.

The numbers of participants and demographic information for each of the activities are shown in Table 1.

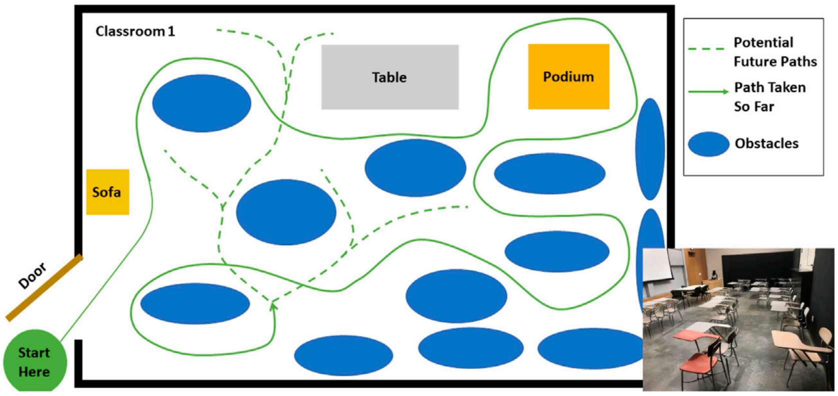

FIGURE 2
Classroom: Architecture of one of the classrooms. The arrangement of obstacles was not controlled and varies across subjects. The subject walked at self-selected speed and along self-selected path, The experimenter directed the subject to change their path only if the subject repeated the same path more than 2 times.

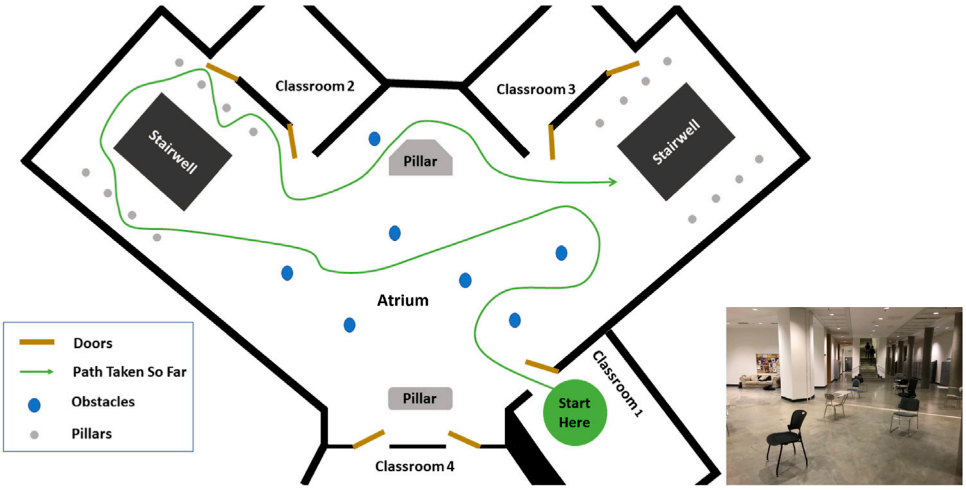

FIGURE 3
Atrium: Architecture of the Atrium. The arrangement of obstacles was not controlled and varies across subjects. The subject walked at self-selected speed and along self-selected path, The experimenter directed the subject to change their path only if the subject repeated the same path more than 2 times.

3.2 Data analysis

In the Background: Complexity Analysis section above, we described three major notions that can be used to analyze complexity: Dimensionality, Variability, and Nonlinear Dynamics. We used measures related to these notions as described below, to analyze the complexity of activities.

3.2.1 Dimensionality

The dimensionality of an activity is defined as the number of PCA principal components required to explain 95% variance in the activity ($N_{95\%}$). We used the function 'pca' from the Statistics and Machine Learning Toolbox. MATLAB 2020b for the analysis. $N_{95\%}$ was computed using the matrix of 18 dimensional time series from each trial. The mean and standard deviation of $N_{95\%}$ across trials are reported for each activity.

3.2.2 Variability

We examined variability according to two different measures. The first is the Determinant of the data covariance matrix. It is not in standard use for human movement analysis, but it is a longstanding way to quantify variance in multidimensional data (Wilks, 1932). The second measure is GaitSD, which measures how variable the gait cycles are from one another (Sangeux et al., 2016). GaitSD is described in Eq. 1.

$$\begin{aligned} X_{ij} &= i^{th} \text{ gait cycle defined over T time instances, T} = 101 \\ X_j &= \frac{1}{N}\sum_{i=1}^{N} X_{ij}, N = \text{number of gait cycles} \\ GVSD^2 &= \frac{\sum_{j=1}^{T}\sum_{i=1}^{N}\left(X_{ij} - X_j\right)^2}{T(N-1)} \\ GaitSD &= \sqrt{\frac{1}{p}\sum_{k=1}^{p} GVSD_k^2}, \text{p (number of joints)} = 18. \end{aligned} \tag{1}$$

Gait cycles were determined using the foot contact data provided by Xsens, and all the joint angles were time normalized to 101 points using the MATLAB command- *'interp1'*.

3.2.3 Nonlinear dynamics

Following methods from (Decker et al., 2010; Busa and van Emmerik, 2016), we used the Largest Lyapunov Exponent (LyE), and Multiscale Entropy (MSE). These measures were calculated using ankle, knee, and hip kinematics in the sagittal plane.

To calculate the LyE, we first reconstructed the state space from one dimensional time series (sagittal ankle, knee, and hip separately), using Takens' theorem (Noakes, 1991). The delay for reconstruction was estimated using Average Mutual Information (AMI) (Fraser and Swinney, 1986). It was set to be the first local minimum of AMI. Embedding dimensions were determined using Global False Nearest Neighbors (GFNN) analysis (Kennel et al., 1992). Embedding dimension was set to the minimum value that satisfied percent false nearest neighbour less than 10%. LyE were then determined using MATLAB's Predictive Maintenance Toolbox. The package calculates LyE using the algorithm developed by (Rosenstein et al., 1993).

Multiscale Entropy is a way to analyze the self-similarity of a one dimensional time series. There are multiple ways to calculate MSE (Humeau-Heurtier, 2015), but here we use a robust variant, Composite multiscale Entropy (CMSE), proposed in (Wu et al., 2013). The Complexity Index (CI) is defined in Eq. 2. m and r were chosen as 2 and 0.2 respectively in accordance with (Bisi et al., 2018) and values of τ ranged from 1 to 20.

$$\begin{aligned} CI &= \sum_{\tau=1}^{N} CMSE(x, \tau, m, r) \\ \tau &= \text{time scale index, N (Total number of time scales)} = 20 \end{aligned} \tag{2}$$

4 Results and discussion

For each of the activities, we calculated the complexity measures of Dimensionality (Figures 4, 5), Variability (Figure 6), and Nonlinear Dynamics (Figures 7, 8). For each of these, we report the relative complexity of the activities and discuss when the results are contradictory or unexpected.

4.1 Dimensionality: Sidestepping is the most complex activity?

Figure 4A shows variance explained across subjects, from PCA of Lower Limb (18 dof) for the different activities. The number of principal components required to explain 95% of the variance ($N_{95\%}$) is shown in Figure 4B. We observe that left and right sidestepping require the most components to explain the variance, while forward walking requires the fewest. Complexity analysis in terms of dimensionality as measured by PCA, then, concludes that sidestepping is the most complex activity while forward straight line walking is the least.

Dimensionality is appealing as a measure of complexity because it aligns with the intuition that a "more complex" task should require more independence among its degrees of freedom. Dimensionality has been successfully used in gait analysis and has aligned with clinical notions of mobility and the scientific notion of synergies (Latash et al., 2007; Rombokas et al., 2012; Steele et al., 2015a). However, in this study we show that using PCA and "variance accounted for" yields counterintuitive results. Although forward walking is measured as least complex, left and right sidestepping arise as the most complex, while navigating freely amongst challenging obstacles, as in the classroom activity, is measured as less complex than unobstructed sidestepping.

This result is surprising because from our experience of life, we understand that avoiding obstacles, navigating challenging terrain, dealing with uncertainty in the environment, etc. should result in more complex movement in Classrooms and Atrium. It should require us to use more degrees of freedom to navigate. This result can be interpreted in two mutually exclusive ways: 1) Even though sidestepping and backward walking are expected to be highly repetitious, they are less practiced, and thus show less coordination between joints. Thus, the data has more degrees of freedom than expected. 2) Alternatively, the result could be interpreted to indicate that PCA should not be used to measure and compare dimensionality when the two datasets have different overall absolute variance (See Figure 5). For example from Figure 4B, we see that Sidestepping has a dimensionality of approximately 11. Now, from Figure 5, we see that 11^{th} PC for Classrooms and Atrium has greater variance that for Sidestepping activities, but is ignored when 95% variance is used as the criterion to decide the dimensionality of data. This highlights the need for further examination of our intuition about the complexity of locomotion activities, and to be aware of these issues when using PCA for measuring the dimensionality of activities.

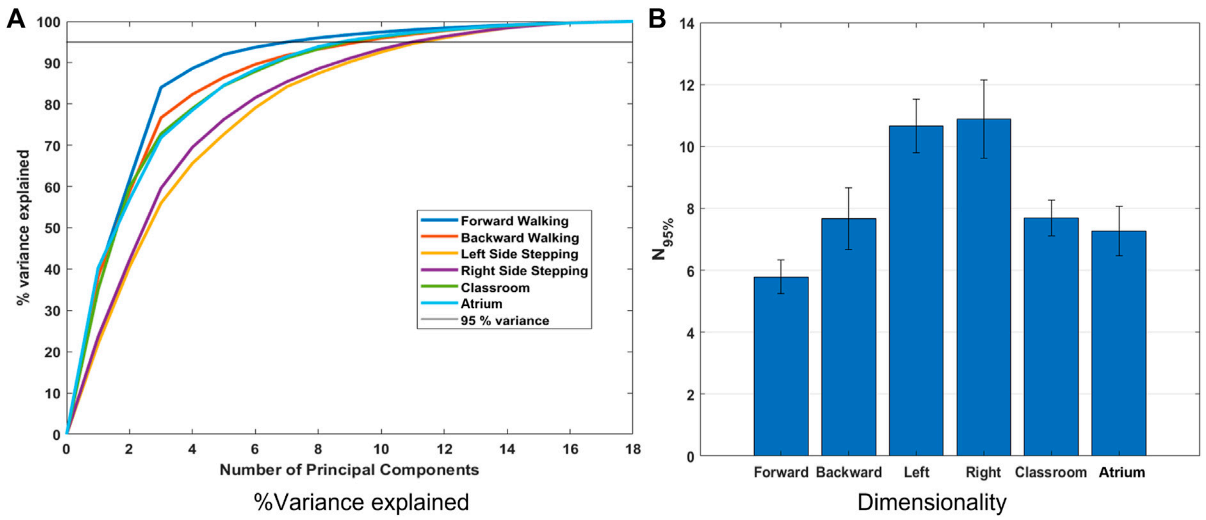

FIGURE 4
(A) Percent variance accounted for by each principal component and the sum of the first n principal components (line plots), for different activities. These were calculated using the data from all subjects. **(B)** $N_{95\%}$ values for all the activities. $\boldsymbol{N_{95\%}}$ is the number of principal components required to explain 95% variance in the data from each subject. $N_{95\%}$ indicates all other activities have higher dimensionality, and therefore complexity, than forward walking. Surprisingly, this metric indicates that left and right sidestepping are more complex than walking in a natural environment.

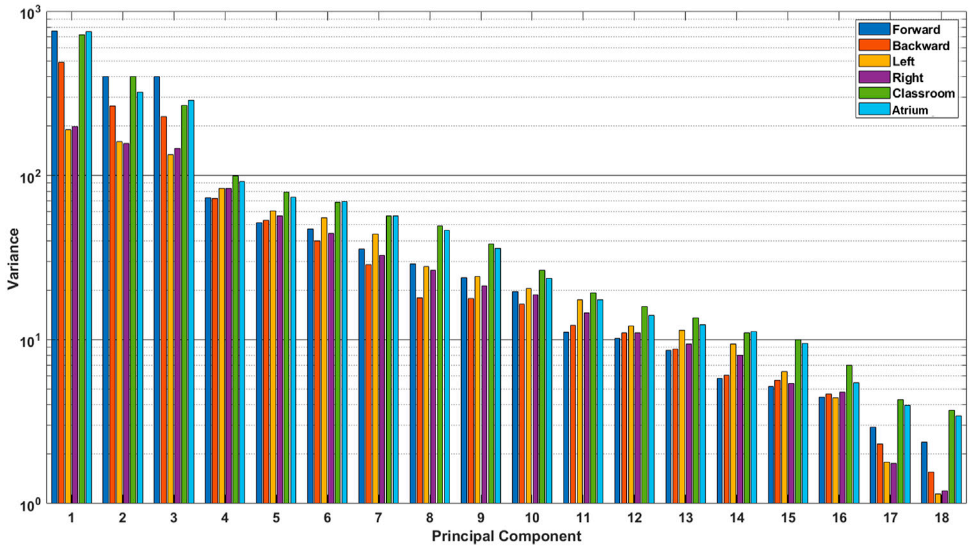

FIGURE 5
Absolute variance accounted for by each principal component, for different activities. These were calculated using the data from all subjects. We see that the last few principal components for Classroom and Atrium show considerably larger amount of variance than sidestepping, even though they are ignored by PCA when measuring dimensionality (see Figure 4).

4.2 Variability: Classroom walking or backward walking is the most complex activity?

Figure 6A shows the generalized variance for the different activities. Forward walking shows the smallest generalized variance indicating tighter coordination of joints, while Classroom shows the largest value, indicating more variability in joint angles and less coordination amongst them. Figure 6B shows that backward walking has the largest GaitSD, indicating greater stride to stride variability of joint kinematics.

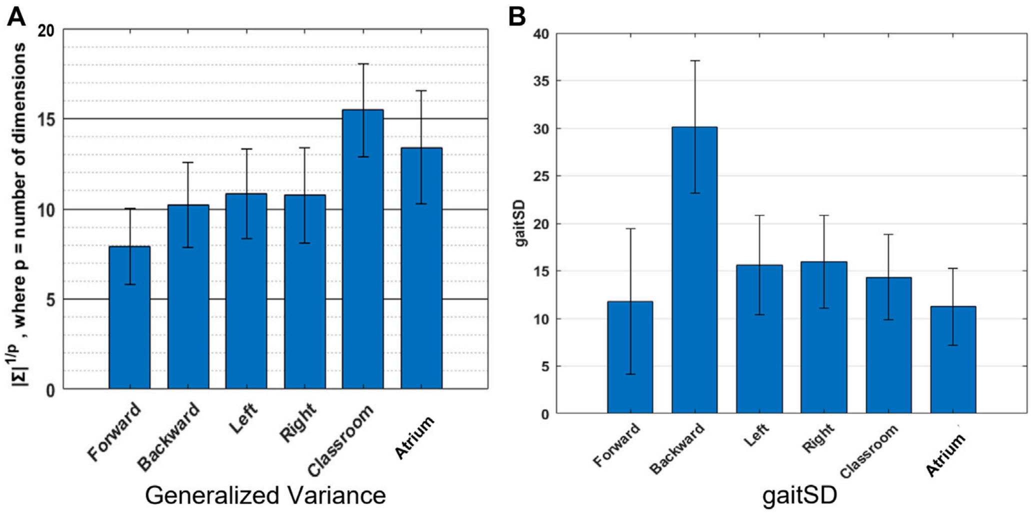

FIGURE 6
Variability: We use two different measures of variability-**(A)** Generalized Variance (geometric mean of the variances along the Principal Components) which measures the spread of the multi-dimensional data. Walking in classroom exhibits greater complexity in the joint angles, than other activties according to this metric, **(B)** GaitSD which measures variability of gait kinematics across strides, ranks backward walking to be of greatest complexities. The values reported are inter-subject mean and standard deviation.

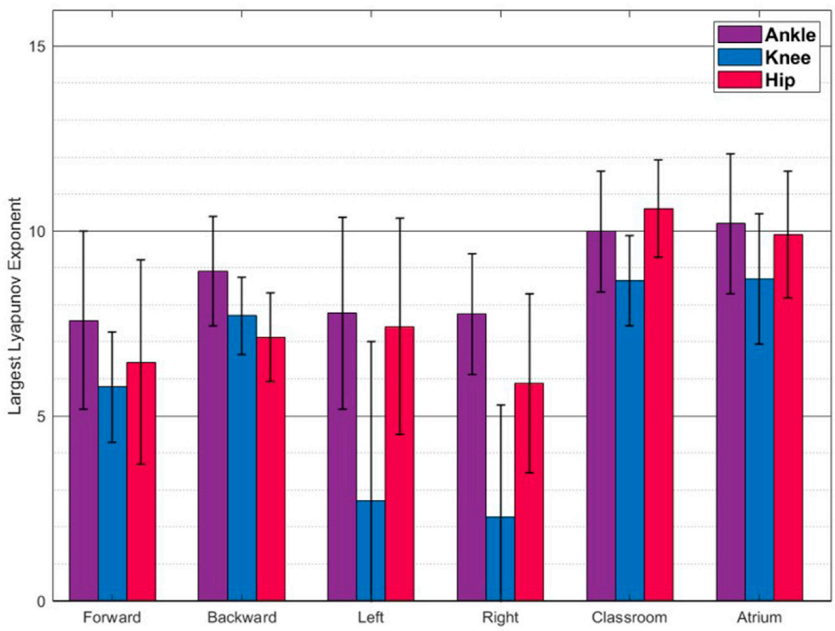

FIGURE 7
Largest Lyapunov Exponent(Mean ± SD) The values reported are mean and standard deviation across the trials from all the subjects. Walking in classrooms and atrium shows greater complexity than other activities.

Variability is a perfectly reasonable way to quantify the complexity of data. While PCA uses variance and covariance to measure complexity, it only looks at how variance is distributed across different dimensions i.e. relative (or percent) variance. It can be instructive to look at absolute variance as well. Here we use generalized variance and GaitSD

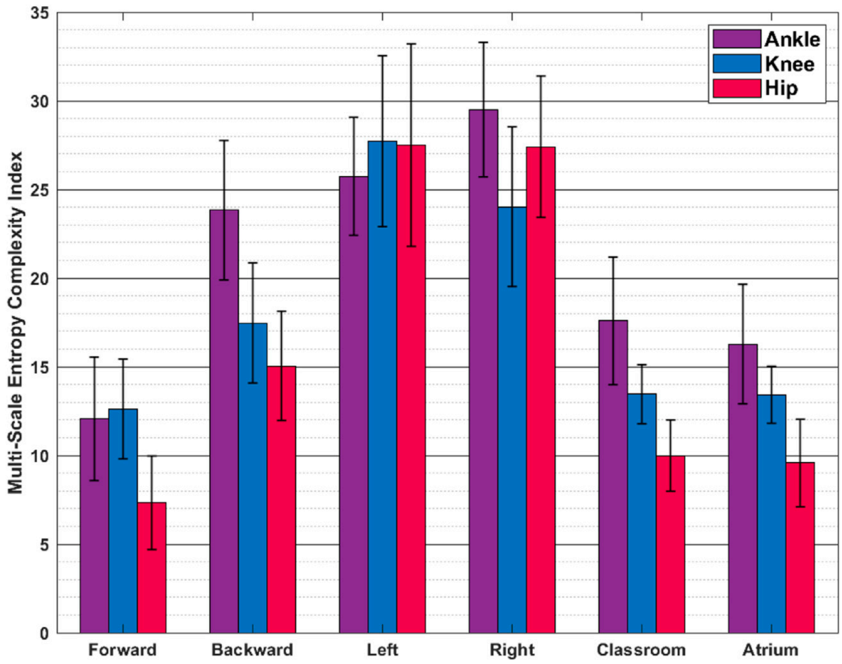

FIGURE 8
Multiscale Entropy (Mean ± SD) The values reported are mean and standard deviation across the trials from all the subjects. Sidestepping shows greater irregularity and thus complexity, than other activities.

to measure variability in two distinct ways. Generalized variance is a measure of how much volume in the state space is occupied by a given activity. In other words how many different configurations of joints are achieved by a given activity. Navigating the Classroom and the Atrium must be expected to show greater generalized variance than other repetitious activities, because they require extemporaneous movements to avoid obstacles, change directions, etc. Generalized Variance comes out to be highest for those activities, matching our expectation.

GaitSD measures the variability of joint angles across gait cycles. It is not sensitive to the amplitude of joint angles (and thus the volume occupied in the joint-space) but instead the deviations at different phases in a gait cycle from the mean gait cycle. In other words, trying to do a repetitious activity but failing to do it exactly would have a greater GaitSD value than doing many kinds of movements but with more precision. This might explain why backward walking has a greater GaitSD value than other activities. Backward walking is presumably less practised in daily life than the other activities. Sidestepping also shows slightly higher values than other regularly practised activities like forward walking, walking in the classrooms and atrium.

This highlights that variability can be measured in different ways but more importantly the different measures need not agree. GaitSD, a measure of gait consistency, rates backward walking to have almost twice the amount of gait variability than unrestricted classroom walking. Further examination is required to understand the mechanisms leading to this observation, because naively we would expect unrestricted classroom and atrium walking to have greater variability than backward walking which is expected to be repetitious.

4.3 Nonlinear dynamics: Classroom or sidestepping is the most complex activity?

Figure 7 shows the LyEs for different activities. For the most part, the activities show positive LyE values indicating non-periodic gait signals. Classroom and Atrium show largest LyE of all the activities, across all the joints. For the knee joint, LyE of sidestepping for some subjects are negative or close to 0, while other subjects have large positive LyE (close to 6). This might be an artifact of noise in the data and needs more investigation. Figure 8 shows the analysis of ankle, knee and hip joint trajectories, using MSE, computed using sample entropy (S_E) over 20 time-scales.

Human gait can be modelled as a dynamical system. Non-linearity in dynamical systems leads to different kinds of complexities than the ones we analyzed above. This has to do with periodicity, regularity and predictability of temporal dynamics of the system. We used LyE and Multi-scale Entropy to analyze complexity from this point of view.

LyE measures how quickly neighbouring trajectories in the dynamical system converge (negative values) or diverge (positive values). Larger positive values indicate faster divergence and thus lesser predictability of gait further into the future. Since, Classroom and Atrium exhibit largest values, they should be expected to be less predictable. This is expected because navigating obstacles would require significant deviation of gait from the immediate history, thus less predictability into the future.

Multi-Scale Entropy measures how many repeating patterns are there in a signal over different time-scales. Intuitively, it measures the regularity, or predictability, of a signal. We see that unusual activities i.e. sidestepping and backward walking show more irregularity in gait than more common activities i.e. forward walking, Classroom and Atrium. This might be a result of lack of practice in sidestepping and backward walking.

Once again we find major disagreement between the two measures used in this analysis, highlighting contradictions between different types of complexities in temporal dynamics.

4.4 Complexity cannot be defined as a unitary concept

These results demonstrate that there are several ways to measure different aspects of data complexity. These measures often do not rank activities similarly. For example, dimensionality as measured using PCA ranks sidestepping to be the most complex, but gait cycle variability as measured using GaitSD ranks backward walking to be the most complex, while divergent nonlinear dynamics as measured using LyE ranks atrium as the most complex. Looking forward for practitioners of movement analysis, *complexity* should probably be avoided as a single concept in favor of specific measures. For example, when we use PCA analysis, we should state that we are measuring degrees of freedom, not accounting for the scale of the variance. We summarize the rankings of complexity in Figure 9. As can be seen, no column, corresponding to activities, is agreed upon in complexity ranking by the different methods.

4.5 Forward walking is the least complex activity

Most of the measures agreed on forward walking being the simplest activity. Although GaitSD and LyE did not strictly rank it as the least complex, it is very close, as can be seen in Figures 6, 7. This is expected since forward walking is highly practiced and repetitious, and does not involve deviations to account for obstacles.

	Forward	Backward	Left	Right	Classroom	Atrium
PCA	6	4	2	1	3	5
Variance	6	5	3	4	1	2
gaitSD	5	1	3	2	4	6
Largest Lyapunov Exponent	4	3	5	6	1	2
Multi-Scale Entropy	6	3	1	2	4	5

Most complex 1 2 3 4 5 6 Least complex

FIGURE 9
Overview of how each complexity measure ranks the six activities. While there are some similarities, it can be seen that each measure is sensitive to different characteristics of the complexity of the data, and that many of the results are surprising or counterintuitive.

4.6 Practical recommendations

- PCA ranks sidestepping to be more complex and backward walking to be as complex as walking around obstacles in classrooms and atrium. This is counterintuitive. On further analysis, we found that sidestepping does not necessarily have more variance in the last PCs than classroom and atrium, as can be seen from Figure 5. This can be understood from the 2D toy example, as shown in Figure 1, bottom row. As can be seen, even if the minor principal component has the same variance for both blue and red clouds, PCA would rank the blue cloud to be more complex than red cloud, because it ignores the absolute variance and only accounts for relative variance. Thus, we need to account for absolute variance, before we use PCA to rank the dimensionality of different activities. To measure the absolute variance, we recommend that researchers use Generalized Variance.
- Usually, in the gait literature, variance is used to analyze one-dimensional signals. In our analysis, we used Generalized Variance as a measure of absolute variance for multi-dimensional data. We found that the resulting complexity ranking of the activities aligned well with our expectations. Thus, we recommend using Generalized Variance to measure the scale of the data.
- In our analysis, we found that Largest Lyapunov Exponent values to be quite different from (Buzzi et al., 2003). This could be attributed to sensitivity of the measure to noise in the data or the length of the data. In addition, computation of Largest Lyapunov Exponent assumes a time-invariant and autonomous dynamical system. Thus, we recommend against the use of the measure, unless the accompanying assumptions are tested for.
- In the gait literature, complexity is an umbrella term that measures different aspects of the data-dimensionality, variance and nonlinear dynamics. Since these measures

do not always agree, we recommend against the usage of the term ‘complexity‘ and instead using the terms that emphasize the metric being used e.g. dimensionality.

5 Limitations

Dimensionality, as a concept used in mathematics, is much broader than we are using it here for gait analysis. For example, dimensionality can be defined as the number of Euclidean dimensions, topological dimensions (Suárez, 1994), fractal dimensions, etc. We only use number of principal components as it has a precedent in gait analysis. Even in terms of integer dimensions or degrees of freedom, other dimentionality reduction techniques like autoencoders could be used to estimate dimensionality (Portnova-Fahreeva et al., 2020; Boe et al., 2021).

Calculation of the Largest Lyapunov exponent requires the assumption that the system is *autonomous,* and time invariant (Sato et al., 1987; Rosenstein et al., 1993). This assumption could be broken by learning effects, fatigue, etc. Additionally the Largest Lyapunov exponent requires large amounts of data to be confidently calculated. So, care must be taken to ensure that adequate data sizes are used. It has been shown that accurate Lyapunov dimension calculation requires hundreds of gait cycles, and can be sensitive to preprocessing choices, such as using a fixed number of strides or a fixed number of data points (Hussain et al., 2020). When comparing activities that have very different total amounts of data, or different standards for preprocessing, care must be taken for this measure to be meaningful. This factor is not limited to Lyapunov dimension for gait; some measures, such as those used in heart rate variability estimation, have been shown to require small data sizes, while others require more data for robust estimation (Chou et al., 2021).

Since the data collection process is time consuming, any particular participant could not perform all of the different activities. While there is no missing data from any particular participant, each performed only a subset of the possible activities, as shown in Figure 1. As a result, the analyses we present here cannot account for individual differences in complexity. Individual gait characteristics could be practically important, for example in designing assistive devices, and should be accounted for also.

The data were also measured for a narrow age range of young people indoors, in an experimental session. We anticipate that their movement was more reflective of their natural patterns for those environments compared to being in a gait analysis laboratory. However, there were still factors that could produce ”demand characteristics” (Rosenthal and Rosnow, 2009). These are changes in behavior due to expectations, whether conscious or not, of the purpose of the experiment or increased conscious control over normally unconscious movements.

Wearable motion capture provides a convenient and versatile means to record movement without instrumentation of the space, but it also is sensitive to challenges in calibration, placement of markers, and precision of recording. There are degrees of freedom with less range of motion that are nonetheless important biomechanically, such as knee and ankle frontal plane, that are measured with less validity than gold-standard marker-based tracking systems.

This analysis does not include statistical significance testing. We have calculated the common complexity measures and reported their mean and standard deviations where appropriate, or other commonly used reports such as percent variance explained in Figure 4A. The large differences or similarities are apparent to see the performance of these measures, but a more formal treatment could include statistical significance testing.

6 Conclusion

In this manuscript, we examine the complexity of different human locomotion activities using various measures of complexity pertaining to dimensionality, variability and nonlinear dynamics. We find that most of the measures rank the most commonly analyzed activity, walking forward in a straight line, to be the least complex. More importantly, different measures disagree about the relative complexity of the remaining activities. Thus, defining complexity as a single notion is challenging and we might need to be cognizant of what aspect of the data we wish to analyze when using any particular measure.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by University of Washington Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

Author contributions

AS and ER contributed to conception and design of the study. AS performed the data analyses. AS and ER prepared the manuscript of this paper. All authors contributed to manuscript revision, read, and approved the submitted

version. ER supervised this research project and provided scientific guidance throughout.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY
Gillian Weir,
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Aden Kittel,
Victoria University, Australia
Edward Hope,
Liverpool John Moores University, United Kingdom
Michael Spittle,
Victoria University, Australia

*CORRESPONDENCE
Jie Mao
maojie@whsu.edu.cn

†These authors have contributed equally to this work

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Effects of video-based training on anticipation and decision-making in football players: A systematic review

Jie Zhao[1†], Qian Gu[2†], Shuo Zhao[3] and Jie Mao[1*]

[1]College of Sports Engineering and Information Technology, Wuhan Sports University, Wuhan, China, [2]School of Physical Education, Shandong University, Jinan, China, [3]Shandong Football Management Center, Jinan, China

The training of athletes' anticipation and decision-making skills has received increasing attention from researchers, who developed and implemented training programs to achieve this. Video-based training (VBT) has become a popular method in anticipation and decision-making skills training. However, little is known about the benefits of implementing VBT in soccer. This systematic review considered the results of studies on VBT aiming to develop decision-making and anticipation skills in football players, and analyzed its effects. Literature published up to March 2022 was systematically searched on the scientific electronic databases Web of Science, PubMed, Scopus, SportDiscus, and Google Scholar. In total, 5,749 articles were identified. After screening the records according to the set exclusion and inclusion criteria, ten articles were considered eligible, including six longitudinal studies and four acute studies. Eight of the ten included studies (80%) showed that VBT group performance in anticipation or decision-making skills was significantly better at post-test than at pre-test, as evidenced by improvements in response accuracy (RA), response times (RT), mean distance scores (MDS) and passing decision-making performance. In six studies that included the no video-based training (NVBT) group, results showed that athletes in the VBT group performed better in anticipation or decision-making skills than in the NVBT group, as evidenced by improvements in RA and RT performance. The studies used different methods for VBT, both explicit and implicit training effectively improved participants' anticipation and decision-making skills. In addition, the implementation of the "first-person" perspective (i.e., the player's perspective) and virtual reality (VR) improved the presentation of video stimuli, effectively improving anticipation and decision-making. The findings of this review suggest that VBT is beneficial in developing anticipation and decision-making judgments in football players. However, some findings were inconsistent with previous studies due to differences in intervention duration and experimental protocols, and further studies are needed. Furthermore, future research should actively seek to design appropriate retention tests and transfer tests to truly understand the benefits of VBT for athletes.

KEYWORDS

video-based training, decision-making, anticipation, performance, football

Introduction

Perceptual-cognitive skills are considered to be executive functions that regulate athletic performance (Vestberg et al., 2012), including visual search (Vaeyens et al., 2007a), anticipation (Muller and Abernethy, 2012), decision-making (Denardi et al., 2017), and pattern recognition (Williams et al., 2012). Perceptual-cognitive skills have been shown to be a defining characteristic of expert performance (Mann et al., 2007). In other words, excellent motor perceptual-cognitive skills promote the formation and development of motor skills, and high levels of spatio-temporal perceptual-cognitive skills can effectively improve performance (Savelsbergh and Van der Kamp, 2000). For example, in a sport like soccer, the opportunity for player action can easily be surrounded (Fajen et al., 2009). Players must move their heads, bodies, and eyes to perceive their surroundings and calibrate their positions, those of their opponents, and those of their teammates (Fradua et al., 1996; Kim et al., 2005). Make the most favorable decision for subsequent actions based on the current situation (Bennett et al., 2019). The perceptual-cognitive processes of anticipation and decision-making are key skills related to performance (Baker et al., 2003). Anticipation is the ability to recognize the outcome of other athletes' movements before they are performed (Williams et al., 2002). Decision-making is the process of finding, differentiating, comparing, and finally choosing a course of action by an individual when cognitively processing a decision-making phenomenon in an uncertain and complex dynamic situation (Causer and Ford, 2014; Silva et al., 2020). Research has shown that experts demonstrate superior anticipation and decision-making skills compared to novices (Mann et al., 2007), allowing them to make decisions faster, better, and more intuitively (Vaeyens et al., 2007b; Roca et al., 2012). Significant differences in the performance of experts and novices in anticipation and decision-making skills help distinguish athletes with different skill levels (Del Villar et al., 2007; Vítor de Assis et al., 2021).

Anticipation and decision-making skills are important requirements for soccer players (Bennett et al., 2019). Because soccer comprises variability and uncertainty (Romeas et al., 2016). The game is intense, the situation on the field is fluid, and players have to react promptly and accurately according to the situation (Rouwen et al., 2005). For example, in soccer, penalty kicks are typically taken at speeds in excess of 75 km/h, which gives goalkeepers only 400 ms to intercept the ball (Kuhn, 1988). With such time constraints, goalkeepers must concentrate on the most important events or sources of information to effectively respond and execute more successful interceptions (Cañal-Bruland et al., 2005). However, in soccer training, coaches tend to focus on physical and tactical skills, while anticipation and decision-making skills, which are often seen as important issues, are rarely trained systematically (Murgia et al., 2014).

Training of athletes in anticipation and decision-making skills typically includes methods such as video-based training (VBT) (Nelson et al., 2014) and game-based training (Davids et al., 2013). Game-based training involves athletes simulating the decision-making process of the game through self-guided discovery (Gabbett et al., 2009; Light et al., 2014). This approach focuses comprehensively on the interaction between tactical knowledge and skill execution, and is an effective means of improving anticipation and decision-making skills (O'Connor et al., 2017). However, this approach is limited by the number of games and the difficulty of organizing and managing efficient games (Kittel et al., 2020). VBT is a common method to overcome these limitations and effectively improve anticipation and decision-making (Engelbrecht et al., 2016). VBT was defined as a specific practice phase in which video is used to present stimuli that require participants' perceptual-cognitive responses (Larkin et al., 2015; Hadlow et al., 2018). Approaches include viewing and simulating video sequences of matches (Ward and Williams, 2003; Farahani et al., 2020), temporal occlusion (Smeeton et al., 2005; Brenton et al., 2016), occlusion of action sequences, feedback to participants on the accuracy of test results (Gorman and Farrow, 2009; Nelson et al., 2014), and directing attention direction through video information (Hagemann et al., 2006). VBT allows learners to practice without actually performing the skill (Larkin et al., 2014). Especially in sports such as soccer, which require prolonged participation, this approach can accelerate the learning of expertise and speed up the process of perception-cognitive development (Page et al., 2019). By using video training, coaches can control some scenarios according to specific needs, allowing injured players to participate in the training and avoiding increasing the physical load of the athletes (Starkes and Lindley, 1994; Horn et al., 2002). Therefore, this form of practice is the most common way to develop athletes' anticipation and decision-making skills.

The researchers noted that VBT tasks need to maintain as much ecological validity as possible (Silva et al., 2021). To achieve this, the proximity of the video simulation environment to real-life should be taken into account when designing training programs (Raab et al., 2019). Hays (1989) used the term "fidelity" to the comparability between simulated tasks and the real world. Common VBT use broadcast video of matches (Craig, 2013). This approach lacks fidelity and is often criticized (Broadbent et al., 2015). To increase the representativeness of existing training tasks, virtual reality (VR) is beginning to be incorporated into training (Panchuk et al., 2018; Page et al., 2019). VR provides a greater sense of immersion for viewers by increasing the visual correspondence of video simulations (Kittel et al., 2020). VR has been identified as a new VBT method (Vignais et al., 2015). In addition, most of the early studies attempted to explicitly teach participants to focus on "information-rich" areas, providing guiding information for their perceptual-cognitive training (Abernethy et al., 1999; Savelsbergh et al., 2002). This type of training is referred to as explicit training. Hanvey (1999) informed goalkeepers of the rules and cues associated with kick position, and their ability to anticipate the direction of the shot is improved through explicit training. However, subsequent studies have tended to use implicit training (Farrow and Abernethy, 2002; Jackson and Farrow, 2005; Masters et al., 2008). Implicit training promotes guiding participants to seek out key sources of information without explicitly stating the relationship between visual stimuli and changes in response requirements (Shafizadeh and Platt, 2012). Magill (1998) and Farrow and Abernethy (2002) have argued that implicit training can more effectively in improving perceptual-cognitive skills and produce lasting perceptual-cognitive learning effects. However, there is still some debate as to which training method is better at improving perceptual-cognitive skills.

Furthermore, the study of perceptual-motor performance from an ecological perspective emphasizes that motor behavior is a coupling between perceptual and motor systems (Davids et al., 2006). In contrast, most VBT does not include complex motor responses (Hagemann et al., 2006; Gorman and Farrow, 2009; Brenton et al., 2016). This limits the link between perceptual and motor processes. In studies of perceptual-cognitive skills, Dicks et al. (2010) examined the motor performance of soccer goalkeepers in laboratory conditions and field conditions and demonstrated that information extraction was different in perception-action coupled and uncoupled tasks. In the perception-action uncoupled condition, the goalkeeper focused more on attending to the action information of the penalty taker rather than the position of the ball. In contrast, in the perception-action coupled task, the goalkeeper pays attention to both the relative actions of the penalty taker and the position of the ball. There are also some studies that pure perceptual-cognitive training is equally effective compared to perceptual-motor training (Farrow and Abernethy, 2002; Hagemann and Memmert, 2006; Ranganathan and Carlton, 2007). Controversy remains regarding the effectiveness of perceptual-cognitive training in the context of separation of action and perception. Subsequent studies have made improvements by adding transfer tests to the task (Gabbett et al., 2008; Rosalie and Müller, 2012; Lorains et al., 2013; Brenton et al., 2019). Transfer tests were used to measure whether performance improvements transfer to real-world competition situations (Starkes and Lindley, 1994). These studies reported that perceptual-cognitive training that did not involve motor responses could improve real-world motor performance (Gabbett et al., 2008; Rosalie and Müller, 2012; Lorains et al., 2013; Brenton et al., 2019). For this reason, it is important that the measurement effect is transferable to the competition (Smeeton et al., 2005; Williams and Ward, 2007). In addition, the researchers suggest that retention tests should be included to determine whether there is a potential lasting benefit to VBT (Schmidt et al., 2018).

In recent years, as research into athletes' perceptual-cognitive skills has continued, there have been some studies showing that VBT can enhance athletes' anticipation and decision-making skills. However, little is known about the benefits of implementing VBT in soccer. Furthermore, to our knowledge, only Larkin et al. (2015) have reviewed VBT to enhance athletes' perceptual-cognitive skills, summarizing the effectiveness of the video-based approach to enhance decision-making skills before 2013. There is a lack of systematic summary of post-2013 research, especially on the implementation of VBT in soccer. Therefore there is a need for a systematic review of this research topic. The purpose of this systematic review is to summarize the effectiveness of VBT to develop anticipation and decision-making judgments in football players, and to analyze various approaches to VBT.

Materials and methods

Our systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Page et al., 2021). We used the Population, Intervention, Comparison, Outcome (PICO) tool to help formulate the research questions (da Costa Santos et al., 2007). "Does VBT improve soccer players' anticipation and decision-making skills more than NVBT or other training? "

Search strategy

We searched the following electronic databases for studies published up to March 2022: Web of Science, PubMed, Scopus, SportDiscus, and Google Scholar. To search the relevant literature as comprehensively as possible, we developed the following on the basis of the above definitions. Search strategy: #1 ("video-feedback" OR "video-based" OR "video-based training" OR "video training"); #2 ("visual function" OR "executive function" OR "attention"); #3 ("decision-making" OR "decision-making training" OR "anticipation" OR "perceptual training" OR "cognitive training" OR "perceptual-cognitive training" OR "Perceptual functions"); #4 ("football" OR "soccer" OR "penalty kick" OR "goalkeepers"); (#1 OR #2 OR #3) AND #4.

Inclusion criteria

The inclusion and exclusion criteria were determined by two authors (JZ and QG) and independently reviewed and evaluated. The inclusion criteria were as follows: (i) the participant group was football players; (ii) the content of the paper focused on training to improve players' perceptual-cognitive skills (i.e., decision-making or anticipation); (iii) video was used as the training stimulus or task; (iv) the article provided information about samples and experimental methods/procedures (e.g., describing data collection procedures, experimental methods, instrumentation, and measures); (v) the article reported the relevant findings of the training; (vi) controlled experiments (interventions with a control group); (vii) intervention studies. The exclusion criteria were as follows: (i) lack of experimental methods and research outcomes; (ii) articles not peer-reviewed; (iii) articles in languages other than English; (iv) non-intervention studies; and (v) designs without control groups.

Extraction of data

Two authors (JZ and QG) independently extracted the following information from the included studies: (i) publication year, location; (ii) number, age, gender, and exercise experience of participants; (iii) measures of intervention, duration; and (iv) study results. Performance outcomes include response accuracy (RA), response times (RT), mean distance score (MDS), and passing decision-making performance. RA is used to test the effect of the intervention on the athlete's anticipation or decision-making RA. RT is used to test the effect of the intervention on the athlete's anticipation or decision-making response times. MDS indicates the distance between the athlete's judged kick position in the test and the actual kick position. Passing decision-making performance is used to test the impact of an intervention on the accuracy of an athlete's technical action in passing. We retrieved RA as a measure of anticipation or decision-making performance if the findings indicated that VBT had a differential impact on anticipation or decision-making performance (e.g., RA improved but RT decreased). The effects of different VBT modalities on perceptual-cognitive skills, including explicit training and implicit training, were also investigated.

Methodological quality

The methodological quality of the included studies was evaluated independently by two authors (JZ and QG). In cases of disagreement, a third author (JM) deliberated until consensus was reached. The methodological quality of the included studies was assessed using the Physiotherapy Evidence Database (PEDro) scale (Elkins et al., 2013). The scale consists of 11 items, namely, eligibility criteria, randomization, concealed allocation, baseline equivalence, blinding of subjects, blinding of instructors, blinding of assessors, retention above 85%, intention to treat analysis, between-group comparison, point measures and measures of variables. Items with a clear description were given 1 point and those without a clear description were given 0 points.

Results

Study selection

Our search of the five scientific electronic databases identified 5,749 titles, from which duplicate and irrelevant articles were removed, leaving 4,173 papers which were filtered by title and abstract. Of these, 61 articles met the inclusion criteria. Two authors (JZ and QG) excluded 51 articles after independently assessing the 61 articles using the predetermined inclusion and exclusion criteria. The remaining 10 studies were eligible for inclusion in this study. **Figure 1** shows the flowchart for the search and selection.

Characteristics of included studies

Overview

Overall, 10 studies were included. Studies were divided into two categories based on the type of intervention: (i) acute studies, defined as interventions lasting less than 24 h ($n = 4$) (Poulter et al., 2005; Nunez et al., 2009; Javier Nunez et al., 2010; Shafizadeh and Platt, 2012); and (ii) longitudinal studies, defined as interventions duration $\geq$ 24 h ($n = 6$) (Gabbett et al., 2008; Savelsbergh et al., 2010; Ryu et al., 2013; Murgia et al., 2014; Nimmerichter et al., 2016; Fortes et al., 2021). The characteristics of the included studies are summarized in **Tables 1**, **2**, respectively. The included studies provided a total of 300 participants (198 males: 66% and 102 females: 34%). The sample size for each study ranged from 16 to 48. The participants ranged in age from 14 to 25 years. These studies were conducted using both pre-test and post-test research designs.

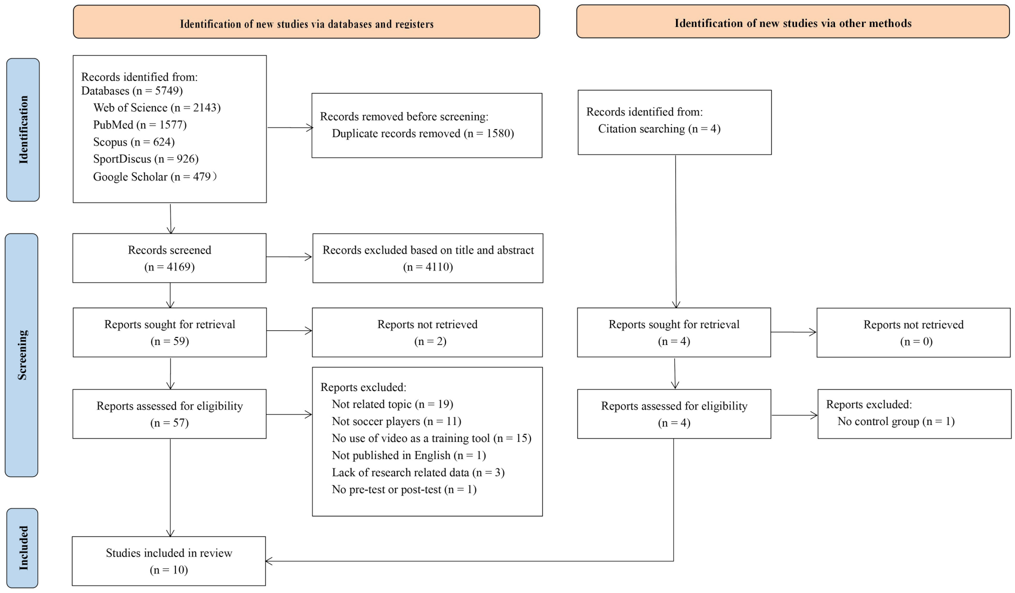

FIGURE 1
Flowchart of search and study selection according to PRISMA guidelines.

Longitudinal studies

In the six longitudinal studies (Gabbett et al., 2008; Savelsbergh et al., 2010; Ryu et al., 2013; Murgia et al., 2014; Nimmerichter et al., 2016; Fortes et al., 2021), the length of the interventions ranged from 6 days to 8 weeks. Four studies involved elite athletes (Gabbett et al., 2008; Murgia et al., 2014; Nimmerichter et al., 2016; Fortes et al., 2021) and two studies involved novices (Savelsbergh et al., 2010; Ryu et al., 2013). One study involving elites used innovative interactive home training that allowed participants the freedom to schedule training cycles without any experimenter supervision (Murgia et al., 2014). The remaining studies were conducted in a laboratory setting and required experimenter supervision or the use of specific equipment (Gabbett et al., 2008; Savelsbergh et al., 2010; Ryu et al., 2013; Nimmerichter et al., 2016; Fortes et al., 2021). Two of the six studies asked participants to perform video training from a "third-person" perspective (i.e., the broadcast perspective) (Gabbett et al., 2008; Murgia et al., 2014), and four asked participants to watch football videos from a "first-person" perspective (i.e., the player's perspective) (Savelsbergh et al., 2010; Ryu et al., 2013; Nimmerichter et al., 2016; Fortes et al., 2021). One study conducted retention tests to examine the effects of skill retention after the training period (Ryu et al., 2013). One study conducted transfer tests to measure the translation of performance improvements into a realistic competition environment (Gabbett et al., 2008).

Acute studies

Among the four acute studies (Poulter et al., 2005; Nunez et al., 2009; Javier Nunez et al., 2010; Shafizadeh and Platt, 2012), one study involved elites athletes (Javier Nunez et al., 2010), two studies involved novices (Poulter et al., 2005; Shafizadeh and Platt, 2012), and one study involved both novices and elites (Nunez et al., 2009). The four studies were conducted in the laboratory and the training program was supervised (Poulter et al., 2005; Nunez et al., 2009; Javier Nunez et al., 2010; Shafizadeh and Platt, 2012). In addition, all four studies required participants to watch football videos from a "first-person" perspective (Poulter et al., 2005; Nunez et al., 2009; Javier Nunez et al., 2010; Shafizadeh and Platt, 2012). One study also conducted retention tests (Javier Nunez et al., 2010).

Methodological quality of included studies

The rating scores for the methodological quality of each study based on the PEDro scale are presented in **Tables 1**, **2**, with a mean score of 6.6 and a range of 5–8 (see **Supplementary Table** for details).

Study findings

Longitudinal studies

Five of the six longitudinal studies (83.3%) showed significant improvements in anticipation or decision-making skills performance in the VBT group at post-test than at pre-test (Gabbett et al., 2008; Ryu et al., 2013; Murgia et al., 2014;

Nimmerichter et al., 2016; Fortes et al., 2021). Five studies that included the NVBT group showed that the VBT group outperformed the NVBT group in anticipation or decision-making skills at post-test (Gabbett et al., 2008; Savelsbergh et al., 2010; Ryu et al., 2013; Murgia et al., 2014; Nimmerichter et al., 2016). In addition, the results of one retention test (Ryu et al., 2013) and one transfer test (Gabbett et al., 2008) were reported. The retention test result showed that the VBT group maintained short-term skill improvements over the NVBT group (Ryu et al., 2013), and the transfer test result reported better transfer of skills in the VBT group than in the NVBT group (Gabbett et al., 2008).

Seven performance outcomes were reported in six longitudinal studies. Four studies included RA as a performance outcome (Gabbett et al., 2008; Savelsbergh et al., 2010; Ryu et al., 2013; Murgia et al., 2014), one study included RA and RT as performance outcomes (Nimmerichter et al., 2016), and one study included passing decision-making skills as a performance outcome (Fortes et al., 2021). Six of the seven outcomes reported significantly improved performance (RA, RT, and passing decision-making skills) in the VBT group and better performance than the NVBT group at post-test (Gabbett et al., 2008; Ryu et al., 2013; Murgia et al., 2014; Nimmerichter et al., 2016; Fortes et al., 2021). One outcome reported better performance (RA) in the VBT group than in the NVBT group at post-test (Savelsbergh et al., 2010). In addition, one transfer test included passing, dribbling, and shooting decision-making skills as performance outcomes (Gabbett et al., 2008). The results showed that the athletes in the VBT group performed better in passing, dribbling and shooting decision-making skills than the athletes in the NVBT group.

Two of the six longitudinal studies examined the effects of implicit training on penalty kick anticipation skills in novice participants (Savelsbergh et al., 2010; Ryu et al., 2013). These two studies reported better anticipation performance in the implicit training group than in the group that did not receive guidance (Savelsbergh et al., 2010; Ryu et al., 2013). In addition, one study included retention tests and showed that the implicit training group maintained short-term skill improvements over the group that did not receive guidance (Ryu et al., 2013). One other study used an immersive 3D video stimulus with elite participants (Fortes et al., 2021). The results showed that the immersive 3D video group had significantly improved passing decision-making skills compared to the 2D video group.

Acute studies

Three of the four acute studies (75%) showed significant improvements in anticipation or decision-making skills performance in the VBT group at post-test than at pre-test (Poulter et al., 2005; Javier Nunez et al., 2010; Shafizadeh and Platt, 2012). One study that included the NVBT group showed that the VBT group outperformed the NVBT group in anticipation or decision-making skills at post-test (Javier Nunez et al., 2010). In addition, the results of one retention test were reported, showing that the retention of skills was superior in the VBT group than in the NVBT group (Javier Nunez et al., 2010).

Six performance outcomes were reported in four acute studies. One study included RA as a performance outcome (Poulter et al., 2005), two studies included RA and RT as performance outcomes (Nunez et al., 2009; Javier Nunez et al., 2010), and one study included MDS as a performance outcome (Shafizadeh and Platt, 2012). One of the six outcomes RA in the VBT group and outperformed the NVBT group at post-test (Savelsbergh et al., 2010). Four outcomes (RA, RT and MDS) in the VBT group (Poulter et al., 2005; Nunez et al., 2009; Shafizadeh and Platt, 2012). One outcome reported a decrease in performance (RT) in the VBT group (Savelsbergh et al., 2010).

Two of the four acute studies examined the effects of explicit training on the performance of penalty kick anticipation skills (Nunez et al., 2009; Shafizadeh and Platt, 2012). One study with novice participants showed an improvement in anticipation performance in the explicit training and the no guidance groups, with the explicit training group outperforming the no guidance group (Shafizadeh and Platt, 2012). One study with novice and elite participants found that the explicit training group performed better in anticipation skills compared to the group that did not receive guidance (Nunez et al., 2009). There was no significant difference in anticipation performance between novices and elites in explicit training.

Of the four acute studies, two compared the effects of implicit and explicit training on the performance of penalty kick anticipation skills (Poulter et al., 2005; Javier Nunez et al., 2010). The results of one study in which participants were novices, showed that the explicit training group improved performance on participant anticipation significantly, while the implicit training group showed no significant change (Poulter et al., 2005). One study with elite participants reported that explicit training improved participants' anticipation performance better than implicit training (Javier Nunez et al., 2010). Retention tests were also conducted in this study and showed that the explicit training group was more effective than the implicit training group in terms of skill retention (Javier Nunez et al., 2010).

Discussion

We review research on video-based perceptual-cognitive training to develop anticipation and decision-making skills in football players. The effectiveness of VBT to improve anticipation and decision-making judgments were analyzed and various training methods used for video tasks were also considered. The findings highlighted several key findings: (i) the available evidence tends to support the positive effects of VBT on improving the anticipation and decision-making skills in football players; (ii) VBT used training methods such as

TABLE 1 Characteristics of the included longitudinal studies.

Study (authors, publication year, methodological quality, location)	*N*	Skill level	VBT		NVBT	Intervention duration/ session length	Testing times	Results
			(1) Gender (2) Age (years) (3) Playing experience (years) (4) Interventions	(1) Gender (2) Age (years) (3) Playing experience (years) (4) Interventions	(1) Gender (2) Age (years) (3) Playing experience (years)			
Gabbett et al. (2008) 6/12 Australia	16	Elite	(1) 8F/8 (2) 18.3 ± 2.8 (3) NA	None	(1) 8F/8 (2) 18.3 ± 2.8 (3) NA	4 weeks	Pre-test; post-test; transfer test	RA of tasks was significantly improved in the VBT group at post-test ($p = 0.05$), and RA of tasks in the NVBT group was not significantly different ($p > 0.05$). Passing, dribbling, and shooting decision-making skills improved in the VBT group in the transfer test, while there was no change in the NVBT group.
Savelsbergh et al. (2010) 7/12 Netherlands	30	Novice	(1) NA (2) 22.0 ± 3.6 (3) 5.7 ± 3.5 (recreational) (4) IT	(1) NA (2) 22.0 ± 3.6 (3) 5.7 ± 3.5 (recreational) (4) UT	(1) NA (2) 22.0 ± 3.6 (3) 5.7 ± 3.5 (recreational)	6 days	Pre-test; post-test	At pre-test, there was no significant difference in RA between the groups of tasks, and the IT group (RA increased by 12.6) performed better at post-test compared to the UT (RA decreased by 2.7) and NVBT groups (RA increased by 3.7). RT of the tasks in the IT group increased at post-test compared to pre-test, with no significant change in the other groups.
Ryu et al. (2013) 7/12 China (Hong Kong)	28	Novice	(1) 9M/9 (2) 22.6 ± 2.7 (3) 0 (4) IT	(1) 10M/10 (2) 22.6 ± 2.7 (3) 0 (4) UT	(1) 9M/9 (2) 22.6 ± 2.7 (3) 0	1 week	Pre-test; post-test; retention test	RA improved significantly better in the IT group than in the NVBT group without impairing RT ($p < 0.001$). RA improved in the IT and UT groups, while the improvement was better in the IT group ($p < 0.001$). In the retention test, RA was better in the IT group than in the other groups.
Murgia et al. (2014) 7/12 Italy	38	Elite	(1) 13M/13 (2) 16.0 ± 1.9 (3) 9.3 ± 2.6	(1) 13M/13 (2) 16.0 ± 1.9 (3) 9.3 ± 2.6 (4) VST	(1) 12M/12 (2) 16.0 ± 1.9 (3) 9.3 ± 2.6	8 weeks	Pre-test; post-test	In the simulated penalty kick task, RA in the horizontal and vertical directions was significantly improved in the VBT group ($p < 0.001$), but not in the VST and NVBT groups.
Nimmerichter et al. (2016) 6/12 Austria	34	Elite	(1) 18M/18 (2) 14.4 ± 0.1 (3) 3–5	None	(1)16M/16 (2) 14.4 ± 0.1 (3) 3–5	6 weeks	Pre-test; post-test	RA and RT of tasks were significantly improved in the VBT group at post-test ($p < 0.001$, $p = 0.006$), and RA was significantly improved by 34% and RT by 24%. While there was no significant change in the NVBT group ($p = 0.125$, $p = 0.297$).
Fortes et al. (2021) 8/12 Brazil	26	Elite	(1) 13F/13 (2) 15.4 ± 0.3 (3) 5.0 ± 1.2 (4) VST	(1) 13F/13 (2) 15.4 ± 0.3 (3) 5.0 ± 1.2 (4) VRT	None	8 weeks	Pre-test; post-test	Passing decision-making skills were improved in the on-field game assessment ($p < 0.005$), and the VRT group showed greater improvement compared to the VST group ($p < 0.005$).

F, female; IT, implicit training; M, male; NA, not available; NVBT, no video-based training; RA, response accuracy; RT, response times; UT, unguided training; VBT, video-based training; VRT, virtual reality training; VST, video-screen training.

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TABLE 2 Characteristics of the included acute studies.

Study (authors, publication year, methodological quality, location)	N	Skill level	VBT				NVBT	Testing times	Results
			(1) Gender (2) Age (years) (3) Playing experience (years) (4) Interventions	(1) Gender (2) Age (years) (3) Playing experience (years) (4) Interventions	(1) Gender (2) Age (years) (3) Playing experience (years) (4) Interventions	(1) Gender (2) Age (years) (3) Playing experience (years) (4) Interventions	(1) Gender (2) Age (years) (3) Playing experience (years)		
Poulter et al. (2005) 7/12 United States	48	Novice	(1) 12F/12 (2) 20.5 ± 4.7 (3) 0 (4) ET	(1) 12F/12 (2) 20.5 ± 4.7 (3) 0 (4) IT	(1) 12F/12 (2) 20.5 ± 4.7 (3) 0 (4) VST	(1) 12F/12 (2) 20.5 ± 4.7 (3) 0 (4) UT	None	Pre-test; post-test	The ET and VST groups showed significant improvement in RA in the horizontal direction at post-test ($p < 0.01$), with greater improvement in the ET (RA increased by 14.86) than in the VST (RA increased by 13.19), and no significant change in the IT and UT groups ($p = 0.20$). There was no significant improvement in RA in the vertical direction for the four groups ($p > 0.05$).
Nunez et al. (2009) 5/12 Spain	20	Elite; novice	(1) NA (2) 25.7 ± 4.2 (3)≥10 (4) ET	(1) NA (2) 22.1 ± 2.5 (3) 0 (4) ET	(1) NA (2) 25.7 ± 4.2 (3)≥10 (4) UT	(1) NA (2) 22.1 ± 2.5 (3) 0 (4) UT	None	Pre-test; post-test	At post-test, the ET elite group had a faster RT compared to the other groups, RT reduced by 102 s. RA was higher in the two ET groups than in the two UT groups, and there was no significant difference between the ET novice group and the ET elite group.
Javier Nunez et al. (2010) 6/12 Spain	32	Elite	(1) 8M/8 (2) 23.2 ± 1.8 (3)≥10 (4) ET	(1) 8M/8 (2) 23.2 ± 2.5 (3) ≥10 (4) IT	(1) 8M/8 (2) 23.2 ± 2.3 (3)≥10 (4) UT	None	(1) 8M/8 (2) 23 ± 2.2 (3)≥10	Pre-test; post-test; retention test	In the simulated penalty kick task, RA was significantly improved in the ET group, with RA increasing by 23.1%, and no significant change was observed in the other groups. RT was significantly increased in the ET and UT groups, and increased by 55 and 112 s, respectively. In both retention tests, RA and RT were higher in the ET group than in the other groups.
Shafizadeh and Platt (2012) 7/12 United States	28	Novice	(1) 14M/14 (2) 19 ± 2.2 (3) ≤2.5 (4) ET	(1) 14M/14 (2) 19 ± 2.2 (3) ≤2.5 (4) UT	None	None	None	Pre-test; post-test	In the simulated penalty kick task, MDS was improved ($p < 0.03$), and the ET group showed greater improvement compared to the UT group.

ET, explicit training; F, female; IT, implicit training; M, male; MDS, mean distance scores; NA, not available; NVBT, no video-based training; RA, response accuracy; RT, response times; UT, unguided training; VBT, video-based training; VST, Video-screen training.

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implicit and explicit training; (iii) researchers improved the presentation of video stimuli during training to effectively improve anticipation and decision-making.

Video-based training to develop the effectiveness of anticipation and decision-making judgments

We reviewed ten studies, including six longitudinal studies (Gabbett et al., 2008; Savelsbergh et al., 2010; Ryu et al., 2013; Murgia et al., 2014; Nimmerichter et al., 2016; Fortes et al., 2021) and four acute studies (Poulter et al., 2005; Nunez et al., 2009; Javier Nunez et al., 2010; Shafizadeh and Platt, 2012). Of these, five studies assessed the effects of VBT on elite skill performance (Gabbett et al., 2008; Javier Nunez et al., 2010; Murgia et al., 2014; Nimmerichter et al., 2016; Fortes et al., 2021), four studies investigated the effects on novice skill performance (Poulter et al., 2005; Savelsbergh et al., 2010; Shafizadeh and Platt, 2012; Ryu et al., 2013), and one study examined both elite and novice athletes (Nunez et al., 2009). Eight of the ten included studies (80%) showed that performance in anticipation or decision-making skills was significantly better in the VBT group at post-test than at pre-test (Poulter et al., 2005; Gabbett et al., 2008; Javier Nunez et al., 2010; Shafizadeh and Platt, 2012; Ryu et al., 2013; Murgia et al., 2014; Nimmerichter et al., 2016; Fortes et al., 2021). Six studies that included the NVBT group reported better performance in anticipation or decision-making skills in the VBT group than in the NVBT group (Gabbett et al., 2008; Javier Nunez et al., 2010; Savelsbergh et al., 2010; Ryu et al., 2013; Murgia et al., 2014; Nimmerichter et al., 2016). Of these, four showed significant improvements in anticipation or decision-making skills performance in the VBT group, while only small but non-significant changes were found in the NVBT group (Gabbett et al., 2008; Javier Nunez et al., 2010; Murgia et al., 2014; Nimmerichter et al., 2016). Two showed that the VBT group performed better than the NVBT group on anticipation or decision-making skills at post-test (Savelsbergh et al., 2010; Ryu et al., 2013). In addition, a study investigating both elites and novices found no significant differences in skill performance between novices and elites (Nunez et al., 2009). VBT helped novices and elites in their anticipation and decision-making skills.

When assessing the effects of VBT on anticipation and decision-making skills in football players, researchers typically report RA and RT as performance outcomes. Eight studies reported RA outcomes and the outcomes showed an improvement in participants' RA performance through VBT (Poulter et al., 2005; Gabbett et al., 2008; Nunez et al., 2009; Javier Nunez et al., 2010; Savelsbergh et al., 2010; Ryu et al., 2013; Murgia et al., 2014; Nimmerichter et al., 2016). In addition to accurate responses, football requires rapid responses. Three studies reported outcomes for RT (Nunez et al., 2009; Javier Nunez et al., 2010; Nimmerichter et al., 2016). Two of the three studies claimed that participants' RT improved through VBT (Nunez et al., 2009; Nimmerichter et al., 2016). The remaining study found a decrease in participants' RT performance (Javier Nunez et al., 2010). We found from this review that the researchers improved the accuracy of the participants' decision-making by guiding them to valid information at key points, resulting in an increase in the time required to respond (Javier Nunez et al., 2010). However, it should be emphasized that VBT is not just about getting players to pay attention to the most useful information. It is also about getting players to learn how to time their attention so that they can accurately grasp the most useful sources of information as they become available (Abernethy et al., 1999; Savelsbergh et al., 2010).

Findings from the included studies showed that VBT can be beneficial in enhancing the anticipation and decision-making skills of football players. Football presents a complex, fluid, and unpredictable situation, and to initiate action quickly, players must concentrate on the most pertinent sources of information or significant occurrences (Harenberg et al., 2021). As a result, there is a high demand on the perceptual-cognitive skills of the athletes. VBT was found to help to promote perceptual-cognitive skills (Larkin et al., 2015), which may explain its advantages in training. In VBT, researchers typically show participants video sequences in which the video stops at a certain decision point, and participants are asked to make a judgment about the direction of the action (hitting, shooting, or throwing) (Williams and Grant, 1999). In this way, only specific elements are perceived, and their attention is drawn to the key stimuli, thus accelerating the development of perceptual mechanisms that help to accurately anticipate the opponent's intention to act and make effective decisions (Nimmerichter et al., 2016).

VBT primarily assesses changes in performance before and after the intervention. However, improvement in performance may be a transient result, and retention tests are required at the end of the study to determine if there is a potentially lasting benefit of VBT. Only two of the included studies included retention tests after training (Javier Nunez et al., 2010; Ryu et al., 2013). These studies showed that VBT maintained short-term skill improvements. Of these, Ryu et al. (2013) conducted a retention test after 24 h and showed that the improvement in performance was maintained after the 24 h interval. Javier Nunez et al. (2010) conducted retention tests at intervals of 1 and 7 days. The results showed that improvements in performance were maintained at both 1 and 7 days, but the decline in acquisition performance gradually became larger as time increased.

Another important aspect of VBT is how performance improvements are transferred to real game situations. The key to this is to design a suitable transfer test for the training task (Lorains et al., 2013; Larkin et al., 2015). This is an important consideration in the study of perceptual-cognitive skills because athletes are ultimately measured by their performance on the court (Luis del Campo et al., 2015). Only one of the included studies included the transfer test to evaluate the likelihood of transferring training effects to real matches (Gabbett et al., 2008). For this purpose, the study organized a small-scale standardized training competition. The researchers coded the athletes' decision-making skills on the field, and a sports scientist assessed the athletes' passing, dribbling and shooting skills. The results of the assessment claimed that the VBT group performed significantly better than the NVBT group in passing, dribbling and shooting decision-making skills (Gabbett et al., 2008). The anticipation or decision-making skills learned through VBT can be applied to the pitch. However, in the other nine studies, the effect of improvement in participants' anticipation and decision-making skills in real matches could not be determined. Although it has been shown that retention tests and transfer tests should be included in video-based tasks, this has rarely been considered. To enhance the evaluation and generalization of the results, it is reasonable to encourage future research to investigate this further.

Different video-based training methods to develop the effectiveness of anticipation and decision-making judgments

Of the included studies, two examined the effects of explicit training on anticipation or decision-making skills (Nunez et al., 2009; Shafizadeh and Platt, 2012). The training involved the experimenter explicitly informing participants about the key cues of the stimulus, allowing participants to concentrate on relevant information and ignore irrelevant information (Nunez et al., 2009; Shafizadeh and Platt, 2012). Two examined the impacts of implicit training on the performance of anticipation or decision-making skills, where participants were asked to watch video clips with highlights and the researchers gave them no instructions other than encouraging them to follow the highlights (Savelsbergh et al., 2010; Ryu et al., 2013). The results reported that the implicit training group outperformed the group that did not receive guidance (Savelsbergh et al., 2010; Ryu et al., 2013). We conclude from these studies that explicit and implicit training is effective. Explicit and implicit training improves the athletes' ability to recognize movement patterns, and allows them to direct their attention to task-relevant information, correctly capture key information in movement scenes, and make effective decisions based on the goals of the game (Gorman and Farrow, 2009; Ryu et al., 2013).

In addition, two of the included studies compared the impacts of explicit and implicit training on skill performance (Poulter et al., 2005; Javier Nunez et al., 2010). The results indicated that explicit training improved participants' performance on anticipation or decision-making skills more than implicit training. These findings are inconsistent with previous studies by Magill (1998) and Smeeton et al. (2005) possibly due to the fact that these two studies were acute studies that should have taken into account the transient nature of the training phase. It is also worth noting that both studies had participants respond using a verbal response format, which may have also limited the improvement in the performance of the implicit training group (Poulter et al., 2005; Javier Nunez et al., 2010). Because this form of response does not include a motor response, this limits the connection between perception and motor processes (Davids et al., 2006).

In summary, the current results suggest that both explicit and implicit training improve participants' anticipation and decision-making performance more than training without guidance. However, more research is required to identify which type of training produces better results on skill performance.

Researchers improve the presentation of video stimuli to effectively enhance anticipation and decision-making

Two of the included studies viewed football video clips from a "third-person" perspective, using videos taken from a fixed position that did not simulate the perspective of the player in the game (Gabbett et al., 2008; Murgia et al., 2014). To improve the fidelity of the video simulation task, in eight studies the opponent was described from the perspective of the participants (Poulter et al., 2005; Nunez et al., 2009; Javier Nunez et al., 2010; Savelsbergh et al., 2010; Shafizadeh and Platt, 2012; Ryu et al., 2013; Nimmerichter et al., 2016; Fortes et al., 2021). These videos were one-on-one situations filmed by athletes wearing helmet cameras from a "first-person" perspective, which represents a dynamic "self-perception" of the game scene (Nimmerichter et al., 2016). "Self-perception" is interpreted as imitating the action of the game as realistically as possible and is key to effective performance (Roca et al., 2011).

Although researchers have worked hard to increase the fidelity of video simulations, discrepancies with real-life remain inevitable. VR can minimize this shortcoming and increase the representativeness of the task (Fortes et al., 2021), and is therefore beginning to be incorporated into training. VR is a 3D computer technology-based simulation that creates a virtual world with multiple sensory experiences, allowing athletes to immerse themselves in it and achieve direct interaction with the virtual environment (Banos et al., 2016). It is important to highlight that there are different types of VR, such as virtual video (Hohmann et al., 2016; Gray, 2017) and 360 VR (Panchuk et al., 2018; Page et al., 2019; Kittel et al., 2021). Virtual video enhances the visual stimulation of participants compared to 2D video, but the limitation of this approach is that participants cannot interact with the environment, which limits perception-action coupling (Vignais et al., 2015). Fortes et al. (2021) used

360VR to stimulate participants' decision-making performance, and the training video was presented through a head-mounted display. 360VR allows participants to interact freely with the environment, adding a visual counterpart to the video simulation (Kittel et al., 2020). The results showed that passing decision-making skills were significantly improved in the 360VR group compared to the 2D video group. We recommend incorporating 360VR into training programs as the presentation in VR is closer to the perception on a real football pitch than 2D video and virtual video, are more immersive, maximize task representation, and effectively improve perceptual-cognitive skills.

Practical implications

Perceptual-cognitive training is an increasingly important topic in the field of sports. The findings of this review found that VBT has a positive effect on improving anticipation and decision-making skills in football players. This approach accelerates the learning of expertise and the development of perceptual mechanisms, and is an effective means of enhancing anticipation and decision-making skills (Nimmerichter et al., 2016). In addition, athletes can train in situations where they are unable to physically train (e.g., injuries) with minimal requirements for equipment and facilities, and may even train at home (Murgia et al., 2014). With the development of video technology, the opportunity to design more immersive and interactive perceptual-cognitive training environments is increasing (Fortes et al., 2021). Unfortunately, in soccer training, coaches tend to focus on physical and tactical training and know little about the benefits of video-based perceptual-cognitive training. We outline the potential benefits of VBT for enhancing perceptual-cognitive skills, which will have practical implications for encouraging the use of video-based approaches in soccer training and improving training methods. From a practical standpoint, coaches can use VBT to complement regular soccer training, thus ensuring that players' motor skills are fully developed.

Strengths and limitations

We systematically reviewed the findings related to the effects of VBT on perceptual-cognitive skills in football, focusing on the development of anticipation and decision-making judgments in athletes with video-based perceptual-cognitive training. Overall, the available evidence tended to support the view that VBT is an effective method to improve athletes' anticipation and decision-making skills. Although we outlined the potential benefits of VBT for perceptual-cognitive skills, it is important to consider the limitations of this review. First, we focused on the training of perceptual-cognitive skills for anticipation and decision-making. Therefore, results from training involving other perceptual-cognitive skills (e.g., visual search, pattern recognition) were excluded. Second, the lack of relevant data from the included studies prevented us from conducting a meta-analysis to quantify the effectiveness of the training. Finally, the language of the included studies was limited to English during the systematic database search, potentially missing some papers published in other languages.

Perspectives and future direction

Based on the findings of this systematic review, we have several recommendations for future research. First, increasing the representativeness of tasks may be a useful direction. As technology develops, other methods, such as virtual video and 360VR, may be considered to be more representative of the actual on-field performance of athletes. Second, future research should also consider the activity conditions that occur in actual matches, such as fatigue, anxiety, and off-field noise. By introducing these potential factors that may affect match performance, the realism of the simulated task can be ensured. Finally, a key consideration when conducting VBT is transferring the effects of the training to on-court performance. Future research should actively design appropriate transfer tests for training tasks and conduct long-term transfer tests whenever possible to truly understand the benefits of perceptual-cognitive skills training.

Conclusion

We systematically reviewed the findings of video-based perceptual-cognitive training to develop anticipation and decision-making skills in football players. Findings tended to support the view that VBT has advantages in developing anticipation and decision-making judgments in football players. Some findings are inconsistent with previous studies due to differences in intervention duration and experimental protocols, and follow-up studies are needed to improve the quality of the evidence. In addition, a formal meta-analysis of the existing studies to quantify the training effectiveness would be a valuable addition to future research.

Author contributions

JZ and JM conceived the study. JZ and QG performed the literature search and screening, data extraction, and methodological quality assessment. JZ wrote the manuscript with the help of JM, QG and SZ. JM supervised the manuscript

and accepted the grant. All authors involved in revising the manuscript and finalizing the final version, have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2022.945067/full#supplementary-material

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EDITED BY
Daniel T. H. Lai,
Victoria University, Australia

REVIEWED BY
Wenjing Quan,
Ningbo University, China
Hanatsu Nagano,
Victoria University, Australia

*CORRESPONDENCE
Steven Van Andel,
Steven.van-Andel@uibk.ac.at

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Whole-body movement analysis using principal component analysis: What is the internal consistency between outcomes originating from the same movement simultaneously recorded with different measurement devices?

Steven Van Andel*, Maurice Mohr, Andreas Schmidt, Inge Werner and Peter Federolf

Department of Sport Science, University of Innsbruck, Innsbruck, Austria

A growing number of studies apply Principal Component Analysis (PCA) on whole-body kinematic data to facilitate an analysis of posture changes in human movement. An unanswered question is, how much the PCA outcomes depend on the chosen measurement device. This study aimed to assess the internal consistency of PCA outcomes from treadmill walking motion capture data simultaneously collected through laboratory-grade optical motion capture and field-suitable inertial-based motion tracking. Data was simultaneously collected using VICON (whole-body plug-in gait marker positions) and Xsens (body segment positions) from 20 participants during 2-min treadmill walking. Using PCA, Principal Movements (PMs) were determined using two commonly used practices: on an individual and a grouped basis. For both, correlation matrices were used to determine internal consistency between outcomes from either measurement system for each PM. Both individual and grouped approach showed excellent internal consistency between outcomes from the two systems among the lower order PMs. For the individual analysis, high correlations were only found along the diagonal of the correlation matrix while the grouped analysis also showed high off-diagonal correlations. These results have important implications for future application of PCA in terms of the independence of the resulting PM data, the way group-differences are expressed in higher-order PMs and the interpretation of movement complexity. Concluding, while PCA-outcomes from the two systems start to deviate in the higher order PMs, excellent internal consistency was found in the lower order PMs which already represent about 98% of the variance in the dataset.

KEYWORDS

3D motion capture, optical motion capture, wearable sensors, inertial measurement units IMU, principal component analysis PCA, principal movements PM, gait, walking

1 Introduction

Human movement emerges through the coordination of our vastly complex motor system. It is one of the main problems in biomechanics and motor control research to determine how this complex system, with an abundance of degrees of freedom, is coordinated and controlled (Bernstein, 1967). Traditionally, researchers have taken the approach to determine measures that summarize the workings of this system by looking at single outcome variables like the Center of Mass or Center of Pressure (Quijoux et al., 2020; Mehdizadeh et al., 2021; Richmond et al., 2021). However, this approach has also been criticized as such a low-dimensional variable inherently cannot contain all information available within a complex (multi-dimensional) system (Federolf et al., 2021). As an alternative to this low-dimensional approach, the use of Principal Component Analysis (PCA) has been gaining traction in the study of whole-body movement control (Troje, 2002; Daffertshofer et al., 2004; Federolf et al., 2012; Federolf, 2016).

Using PCA, one decomposes the variance in high-dimensional, complex signals into a set of principal component (PC) vectors, each explaining a portion of the total variance. As input for a PCA on human movement, many recent studies have been using body-segment locations represented by marker positions (Federolf et al., 2012; Ross et al., 2018; Armstrong et al., 2021; Mohr et al., 2021). For example, when collecting movement data using a 39-marker full-body marker set, this results in a 117-dimensional input matrix for the PCA (39 markers with an x, y and z dimension). By determining linear relations within this high-dimensional matrix, PCA determines PC vectors, which are orthogonal to each other. The first PC (i.e., PC1) constitutes the vector that can explain the most variance, followed by PC2, PC3 and so on. In this way, the lower-ranked PCs cover the main movement components, sometimes interpreted as main movement strategies (Federolf et al., 2013b). For instance in bipedal postural control, these have been shown to closely approximate whole-body movements such as the ankle and hip strategy (Federolf et al., 2013b). These PC-vectors and the component of the movement they represent are known as “Principal Movements” (PMs; Federolf, 2016).

In gait, PCA has been frequently applied to decompose whole-body movement patterns into separate PMs (Ó′ Reilly, 2021; Promsri, 2022; Stetter et al., 2020; Zago et al., 2022). For example, in treadmill walking, it is typically seen that only a few PMs are needed to explain most of the variance in the movement (Andel et al., 2022; Malloggi et al., 2021; Ó’Reilly & Federolf, 2021). Federolf et al. (2012) determined that already 84.2% of variance could be explained by PM1, representing anterior-posterior arm and leg movement and only one other PM was required to reach more than 90% explained variance (i.e., PM2; 6.6%, representing knee flexion-extension and vertical body movement).

Applying PCA in human movement analysis holds some considerable advantages: 1) the method allows a non-reductionist approach to biomechanical analysis. Previous studies have criticized traditional biomechanical approaches for their reductionist focus (Federolf et al., 2013a, Federolf et al., 2021); trying to understand phenomena such as sports performance or injury risk by focusing on a limited number of variables. Recently, it has been reasoned that movement can only be fully understood as a whole-body system interacting within a surrounding environment (Pinder et al., 2011; Seifert et al., 2013; Andel et al., 2021; Bolt et al., 2021). PCA is very well suited for this purpose, since it provides a coordinate system for complex movements aligned with the variance created through the movement. In this coordinate system, each coordinate axis/basis vector/PC vector/PM explains a known fraction of the variance in the data (eigenvalue). Thus, the complexity of the system can be resembled as precise as required by the research question. 2) PCA is a data-driven method: no *a priori* decisions have to be taken by the researcher, all available information about the system can enter the analysis, thus reducing the investigator bias and the risk of missing an important variable that would have been essential for understanding an underlying mechanism.

As introduced above, PCA provides a non-biased, holistic approach to human movement analysis. However, to fully benefit from these advantages, it is important to also foster the ecological validity and design experiments as close to the performance situation as possible. Here lies one of the limitations in current applications of PCA. That is, while our ability to collect data in the field has increased drastically in recent years through the development of wearable sensors, these wearables have so far found little application in on-field whole-body motion analysis. As such, it is currently unclear whether the results established using laboratory-grade motion capture technology can be generalized or compared with data collected in the field. It is currently unknown whether PCA outcomes determined using different systems are still comparable. Inherent differences should be expected between outcomes, because of the different numbers of markers or measured segments in the analysis, but to what extend this influences the information within the PMs and the outcomes of the analysis is so far unknown.

This study aims to assess the comparability between Principal Movement outcomes, simultaneously collected from the same movement using two different measurement systems. Thereto, we collect kinematic movement data from the same movement (walking on a treadmill) with two independent measurement systems, then independently perform PCAs on the respective datasets, and finally correlate the resultant time series. If the independently obtained PMs represent the same movement pattern, then they carry the same information and correlation coefficients should be close to 1 (±1) for PMs of the same order (hypothesis H1) and close to 0 otherwise (hypothesis H2). We expect that particularly the lower-order PMs, i.e., the main movement patterns, should show this result, while for higher-order movement patterns, the two PCA systems might start to deviate in how the movement information is represented in the PMs. Therefore, for higher-order PMs, we expect to find increasing deviations from 1 on the diagonal of the correlation matrix and increasing deviations from 0 outside the diagonal (hypothesis H3). Finally, PCAs can be calculated separately for each individual, with the disadvantage that resultant PMs cannot be compared between individual volunteers or–after an appropriate normalization (Federolf, 2016; Gløersen et al., 2018)—a single PCA can be calculated on the normalized and concatenated data of all subjects. The latter approach has the advantage of direct comparability of PMs between different participants, but has the disadvantage that the overall PMs are less precisely aligned with individual movement characteristics. Therefore, we conducted our analysis twice, once by calculating the PCAs separately for each individual ($_{individual}$PCA) and once for the whole group ($_{group}$PCA). We hypothesize (hypothesis H4) that the predicted deviations for higher-order PMs (according to hypothesis H3) will occur earlier (at lower PM order) in the $_{group}$PMs compared to the $_{individual}$PMs due to the individual differences in movement strategy (hypothesis H4).

2 Methods

2.1 Participants

Twenty-three participants (13 females) were recruited from the University of Innsbruck student body to be part of this study (average age ± SD: 25.7 ± 4 years; average height ± SD: 175 ± 9 cm; average leg length ± SD: 92 ± 5 cm). All participants were healthy and free of lower limb injuries for at least 6 months before the measurements. Data from three participants had to be excluded from the analysis due to measurement errors, leading to a final sample of N = 20 participants. The protocol of the study was approved by the institutional ethics board (reference number 40/2020) and all volunteers provided written informed consent prior to participation in the study.

2.2 Materials and protocol

Participants were equipped for data collection with two separate motion capture systems. First, participants donned a lycra full-body Xsens Link suit with 17 inertial measurement units recording at 240 Hz, distributed over the body (Xsens Technologies, the Netherlands). Second, participants' movements were recorded using 10 Vicon Bonita infrared cameras at 250 Hz, from 39 reflective markers positioned on top of the lycra suit according to the full-body plugin gait marker position scheme (Vicon Motion Systems, United Kingdom). The x-axis of the Vicon global coordinate system was aligned with the walking direction on the treadmill.

The measurement protocol started with completing a calibration following manufacturer guidelines (Xsens: N-pose and walk protocol, Vicon Nexus: range of motion protocol). After starting data collection in both systems, the participants clapped their hands together to create a recognizable timepoint in both data streams used for an initial synchronization (a precise synchronization was achieved through cross-correlation, as described later). Then, the participant stepped onto a treadmill, which was moving at 4 km/h. Once the participant settled into a steady gait pattern, data was recorded for 2 min.

2.2.1 Data processing

The analysis was aimed at assessing correlations between the data resulting from the two measurement systems, recorded simultaneously during a single bout of activity. To this end, the following data processing steps were implemented.

Data resulting from the Xsens system was processed using MVN Analyze software (Xsens Technologies, the Netherlands) in the "High Definition" mode and "No-level" processing scenario and exported to be further analyzed in Matlab (2019a, the Mathworks, United States). The resulting raw Xsens data presents with the pelvis segment as origin and the x axis in accordance with the orientation of the feet at calibration. To make this consistent across participants and comparable to the VICON system, data was rotated using a custom Matlab algorithm to align the x axis with the direction of walking. Furthermore, Xsens data was resampled from 240 Hz to 250 Hz for consistency between systems. Using the synchronization event that was identifiable in both data streams, data was cut to a portion of 110s of steady state walking to mitigate the effects of stepping on and off the treadmill.

Vicon data were gap-filled using Vicon Nexus software (Vicon Motion Systems, United Kingdom) and exported for further analysis in Matlab. The origin of the data was reset to a position between the two posterior superior iliac spine markers to create a local refence system similar to the pelvis-centered Xsens data. Identification of the synchronization event was used to identify the same 110s of data, which were then exported for further analysis.

As a result of this procedure, for each participant we obtained two independently measured datasets from the same movement, one available as Vicon marker position data and one available as body segment position data exported from XSens. The data processing steps explained in the next paragraphs were executed in parallel on both of these datasets to obtain 2 sets of PMs; ${}^{Vicon}PM_k$ and ${}^{Xsens}PM_k$; where k indicates the order), whose correlation provided a measure of internal consistency of PMs originating from differing measurements.

Further analysis was performed in two common forms of applying PCA to human movement data: an individual as well as a group-level analysis. For both, the PMs were calculated using a Matlab-based software application named *PMAnalyzer* (Haid et al., 2019) following the normalization and analysis steps outlined in the next sections.

2.2.2 Individual-level analysis

Performing separate PCAs for the data of each participant has the advantage that the PC-eigenvectors are optimally aligned with the variance in the specific dataset, i.e., the PMs are optimally aligned with the specific movements of this individual person. A disadvantage is that for every participant a unique coordinate system is created, which means that the PMs are not comparable between individuals, which limits quantitative analyses of differences between individuals or groups.

For the individual-level analysis, each of the 20 participants provided a 27500-by-117 ^{Vicon}Data matrix [110 s* 250fps x 39 3D marker coordinates] and a 27,500-by-69 ^{Xsens}Data matrix [110 s* 250fps x 23 3D segment position coordinates]. For each participant, both of these matrices were each submitted to a PCA computation to obtain ${}^{Vicon}_{individual}PM_k$ and ${}^{Xsens}_{individual}PM_k$, which were then correlated to obtain 20 correlation matrices ${}_{individual}R$. Specifically, the first-order PMs, ${}^{Vicon}PM_1$ and ${}^{Xsens}PM_1$ were cross-correlated to obtain best possible time synchronization and the obtained time lag was then applied to all other correlation calculations.

2.2.3 Group-level analysis

After appropriate normalization, data matrices of all participants can be concatenated and submitted together to one common PCA analysis (Federolf, 2016). The advantage of this approach is that the resultant PMs are universal to all participants; consequently, quantitative comparisons of the movement patterns between individuals or between groups of participants become possible. One disadvantage is that these general coordinate axes are now not perfectly aligned with the variance (i.e., the movement structure) within each individual.

Mean Euclidian distances (Federolf et al., 2013b) were used to normalize both data matrices from each individual. Then the data matrices from all volunteers were concatenated to form one single 550000-by-117 input ^{Vicon}Data matrix and one single 550000-by-69 input ^{Xsens}Data matrix. After calculating the PCA and projecting the data onto the eigenvectors, the resultant scores were split into separate PMs for each participant: ${}^{Vicon}_{group}PM_k$ and ${}^{Xsens}_{group}PM_k$. Correlating these PMs, using the same time lags as in the individual-level analysis, yielded the group-level correlation matrices ${}_{group}R$.

2.2.4 Correlation analysis

To assess the hypotheses stated for the current paper, correlation matrices for the first 16 PMs [k = 1...16] were calculated in both analyses. Note, that the "correlation matrices" ${}_{individual}R$ and ${}_{group}R$ are not symmetrical since they represent correlations of not the same variables, but correlations between corresponding variables in the other PM matrix; for example, position 2,1 in ${}_{individual}R$ is the correlation between ${}^{Vicon}PM_1$ and ${}^{Xsens}PM_2$, whereas position 1,2 is the correlation coefficient of ${}^{Vicon}PM_2$ with ${}^{Xsens}PM_1$. Matrices presenting the mean of the absolute values for the individual correlation coefficientmatrices (averaged over the 20 participants) are presented in the results.

3 Results

Figures 1, 2 show the averaged matrices ${}_{individual}R$ and ${}_{group}R$, respectively, where the cell background is colored to provide a visual impression of the correlation results. Figure 1 shows that for the individual analysis, there is a near perfect correlation in the first PC-pair (r greater than 0.999) and still a good agreement in the next four PC-pairs (r greater than 0.67). From the fifth PC-pair on, information appears differently distributed, i.e., the information represented in one PM in the one system is distributed over multiple PMs in the other system.

Figure 2 shows that for the group PCA approach correlations appear more distributed. That is, higher correlations (up to about 0.6) appear more often further away from the diagonal. However, the agreement on the diagonal also appears very good, with the first four PC-pairs correlating greater than 0.95 and the first 6 being correlated greater than 0.78.

4 Discussion

The current study investigated internal consistency of PM variables when they are obtained from different measurement systems: a lab-based optical marker tracking system and a wearable IMU system suitable for any environment. Our results demonstrate near perfect internal consistency of the first PM. Correlations of $r = 0.999$ indicate that PM_1 derived from either measurement system contain the same information about the participants' movements. This was true for both approaches to calculating the PCA. Further, for PMs 2 to 4 in the individual-level analysis and for PMs 2 to 6 in the group-level analysis very good internal consistency was observed within PMs of the same order ($r > 0.78$), confirming hypothesis H1. It should be noted, that these 4 and 6 PMs already represented about 98% of the total movement variance in both PCA types, suggesting that together they provide very close approximations of the analyzed movements.

In the individual-level analysis we also find hypotheses H2 and H3 largely confirmed. Correlation coefficients off the diagonal were

Cummulative Variance	Xsens Principal Movements 83,6%	91,7%	97,9%	98,5%	98,9%	99,1%	99,3%	99,5%	99,6%	99,7%	99,7%	99,8%	99,8%	99,9%	99,9%	99,9%
VICON Principal Movements 84,6%	0,999	0,010	0,007	0,004	0,010	0,010	0,007	0,006	0,004	0,008	0,008	0,005	0,003	0,003	0,003	0,003
92,4%	0,010	0,937	0,181	0,022	0,050	0,025	0,012	0,011	0,009	0,012	0,007	0,008	0,006	0,005	0,009	0,006
97,3%	0,008	0,181	0,935	0,061	0,033	0,019	0,016	0,017	0,015	0,015	0,009	0,010	0,009	0,006	0,006	0,007
98,1%	0,004	0,024	0,048	0,859	0,230	0,112	0,093	0,089	0,095	0,062	0,053	0,042	0,032	0,020	0,019	0,017
98,5%	0,008	0,041	0,031	0,220	0,679	0,331	0,160	0,093	0,109	0,074	0,073	0,046	0,049	0,035	0,040	0,041
98,8%	0,007	0,025	0,029	0,130	0,312	0,453	0,440	0,163	0,142	0,125	0,092	0,108	0,061	0,059	0,070	0,045
99,1%	0,011	0,019	0,024	0,090	0,197	0,446	0,396	0,260	0,184	0,166	0,106	0,117	0,073	0,065	0,067	0,061
99,2%	0,007	0,013	0,020	0,089	0,094	0,213	0,311	0,331	0,389	0,190	0,187	0,151	0,143	0,104	0,098	0,087
99,4%	0,006	0,009	0,018	0,091	0,061	0,103	0,231	0,346	0,292	0,309	0,224	0,165	0,102	0,141	0,083	0,105
99,5%	0,008	0,007	0,020	0,065	0,068	0,120	0,151	0,267	0,382	0,332	0,220	0,212	0,157	0,117	0,145	0,072
99,6%	0,007	0,009	0,014	0,063	0,055	0,082	0,095	0,179	0,269	0,287	0,273	0,294	0,232	0,151	0,146	0,147
99,7%	0,007	0,008	0,011	0,037	0,061	0,079	0,080	0,186	0,100	0,265	0,365	0,223	0,351	0,207	0,119	0,137
99,7%	0,004	0,012	0,008	0,032	0,070	0,078	0,091	0,117	0,150	0,247	0,253	0,247	0,297	0,370	0,171	0,114
99,8%	0,004	0,007	0,007	0,025	0,048	0,070	0,097	0,100	0,108	0,178	0,260	0,241	0,210	0,341	0,246	0,229
99,8%	0,003	0,009	0,007	0,035	0,045	0,045	0,068	0,144	0,101	0,169	0,182	0,280	0,260	0,210	0,254	0,230
99,8%	0,002	0,006	0,009	0,016	0,029	0,033	0,058	0,077	0,059	0,117	0,143	0,121	0,134	0,288	0,375	0,342

FIGURE 1
Matrix $_{individual}R$ of the correlation coefficients between ${}^{Vicon}_{individual}PM_k$ and ${}^{Xsens}_{individual}PM_k$. The correlation coefficients shown here represent the mean absolute correlation coefficients averaged over the subject group.

Cummulative Variance	Xsens Principal Movements 81,9%	89,5%	96,1%	97,1%	97,7%	98,3%	98,5%	98,8%	99,0%	99,1%	99,3%	99,4%	99,6%	99,7%	99,7%	99,8%
VICON Principal Movements 82,2%	0,999	0,6901	0,0924	0,6848	0,3585	0,5038	0,4061	0,5345	0,5682	0,4492	0,3737	0,2736	0,4828	0,4137	0,2291	0,468
89,9%	0,7398	0,992	0,0871	0,6317	0,292	0,4132	0,348	0,4327	0,5298	0,3808	0,319	0,2435	0,4839	0,3809	0,2319	0,4405
94,9%	0,1034	0,1022	0,9942	0,1125	0,8025	0,5235	0,1347	0,1945	0,2053	0,2529	0,3138	0,3372	0,2052	0,1752	0,6059	0,3036
96,4%	0,6811	0,6235	0,0883	0,9667	0,2671	0,3853	0,3484	0,4498	0,4094	0,3151	0,2837	0,2	0,3859	0,317	0,1895	0,3471
97,3%	0,5515	0,509	0,3807	0,4227	0,7803	0,6138	0,3117	0,3695	0,3325	0,2728	0,3337	0,2531	0,3564	0,3048	0,3371	0,3281
97,8%	0,2345	0,2257	0,8524	0,1852	0,5968	0,782	0,1615	0,2263	0,2501	0,2557	0,3433	0,356	0,2128	0,2312	0,5832	0,2846
98,2%	0,6211	0,532	0,1457	0,4163	0,2765	0,3399	0,4621	0,461	0,5969	0,3258	0,2808	0,1896	0,3345	0,3138	0,1978	0,4134
98,4%	0,383	0,4139	0,275	0,3298	0,2893	0,3206	0,4689	0,513	0,4147	0,3007	0,306	0,3448	0,5736	0,2536	0,3628	0,3278
98,6%	0,2974	0,2663	0,4239	0,2571	0,4033	0,3628	0,4251	0,4059	0,3294	0,3214	0,4178	0,2462	0,3096	0,271	0,5696	0,2823
98,8%	0,3796	0,3425	0,1845	0,3216	0,2261	0,2355	0,6235	0,5317	0,4475	0,2987	0,2177	0,176	0,4772	0,2432	0,2525	0,3224
99,0%	0,2818	0,2216	0,2072	0,2394	0,2367	0,2953	0,2584	0,2279	0,2676	0,3398	0,4446	0,5437	0,3908	0,2833	0,2347	0,2557
99,1%	0,2114	0,2299	0,3049	0,1947	0,323	0,2865	0,2613	0,2085	0,2817	0,5214	0,3454	0,5872	0,2584	0,3162	0,2934	0,1895
99,3%	0,4001	0,3331	0,2365	0,3447	0,3341	0,353	0,2592	0,2874	0,2739	0,3414	0,2576	0,324	0,2831	0,6846	0,3191	0,3218
99,4%	0,4144	0,4535	0,2147	0,329	0,2236	0,3164	0,4951	0,4471	0,4812	0,2171	0,2581	0,3333	0,4033	0,3847	0,3475	0,2971
99,5%	0,3801	0,3792	0,2648	0,3391	0,2292	0,2852	0,3717	0,3624	0,3648	0,388	0,2038	0,2468	0,3139	0,1857	0,266	0,6351
99,5%	0,2979	0,2939	0,2989	0,2368	0,3061	0,2718	0,2418	0,316	0,2311	0,4341	0,2695	0,352	0,2869	0,2163	0,2735	0,3052

FIGURE 2
Matrix $_{group}R$ of the correlation coefficients between ${}^{Vicon}_{group}PM_k$ and ${}^{Xsens}_{group}PM_k$. The correlation coefficients shown here represent the mean absolute correlation coefficients averaged over the subject group.

close to zero (H2) and for PMs of higher order we find moderate correlation coefficients distributed around the diagonal, suggesting that information represented in one specific PM in one coordinate system is expressed in several PMs in the other coordinate system (H3). Several explanations can be given for H3 and for the observation that the off-diagonal correlation coefficients were not exactly zero. An obvious explanation is that the coordinate systems are not based on the same data in the first place: one data set consisted of reference markers placed on the volunteers' bodies and one consisted of body segments centers obtained as output of a biomechanical model. Another explanation likely playing a role is that it is impossible to perfectly align the coordinate systems in which the PCA input data were expressed. Particularly the fact that the origins of these coordinate systems are not identical–and probably suffer from relative movements between them–is likely a source for the H3 observation and for the discrepancies to H2.

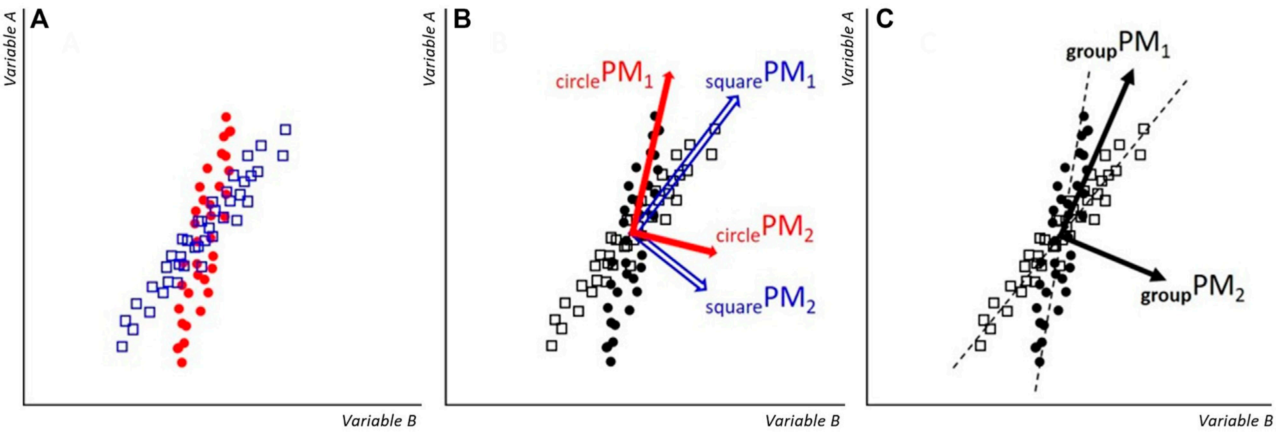

FIGURE 3
Schematic: **(A)** example datapoints of 'Variable A' and 'Variable B' from volunteers "square" and "circle". Since they perform the movement not in exactly the same way, the orientation of the data point clouds are slightly rotated against each other. **(B)** When individual-level PMs are calculated, then each PM-coordinate system aligns with the orientation of the specific data cloud. Thus, the correlation between PM_1 and PM_2 will be zero for the data of each volunteer. **(C)** Group-level PMs are calculated for the entire dataset. For each volunteer, $_{group}PM_1$ is a close approximation of the main movement pattern, however, a small fraction of the volunteer's main movement pattern also gets projected onto $_{group}PM_2$. Therefore, if correlations between PM_1 and PM_2 are calculated for volunteers separately, non-zero correlation coefficients are obtained, specifically, here a positive correlation results for the squares and a negative correlation for the circles.

The results from the group-level analysis were, at first glance, more surprising. Most notable, for this approach to calculate the PCA, H2 was not confirmed. Moderate and large correlation coefficients were found off the diagonal in all areas of the correlation matrix. We did expect (hypothesis H4) that deviations from zero in the off-diagonal correlations would occur earlier (at lower-order PMs) compared to individual-level analysis, however, we already found such deviations in correlations with $_{group}PM_1$. In a PCA, the resultant eigenvectors are orthogonal (correlations performed over the whole group did in fact result in off-diagonal correlations close to zero, as expected). Therefore, the larger off-diagonal correlation coefficients in $_{group}R$ have to be a result of separating the concatenated data back into volunteer submatrices after projecting the data onto the $_{group}$PMs. The correlations can be explained when considering that different volunteers perform the "same" movement slightly differently, as schematically explained in Figure 3. If this is the main driver behind the larger off-diagonal correlations in the group-analysis, then the same pattern should emerge when computing correlations between PMs of a single measurement system, after separating the concatenated data into separate volunteer-submatrices. Indeed, this prediction was supported by our data (Supplementary Figure S1), corroborating the proposed mechanism.

This property of between-PM correlations in a group-level PCA has important generalizable implications for future applications of PCA. First, when performing a group-level analysis, despite the orthogonality between PC-eigenvectors, independence between PMs of different order cannot be assumed. This is a relevant finding, for example with implications for when evaluating PM data using statistical procedures where independence is an assumption. Furthermore, if a whole group of participants perform a movement systematically different compared to another group, then it is likely that differences in movement strategy can be observed in a higher-order PM. One good example for such opposite behavior can be found in Mohr et al. (2021), where differences in running between the sexes were analyzed and directly opposite behavior of the sexes was in fact found in PM_8.

PCA offers the opportunity to assess the complexity of a movement pattern, in terms of the dimensionality of the observed movement. That is, if a movement can be accurately summarized by only one PM (e.g., PM_1 explains a high share of the variance, for example 90%), the movement can be considered less complex than when PM_1 to PM_4 are required to reach the same level of explained variance. The current results offer important considerations for this definition of complexity. When using the individual analysis, the explained variance of the lower order PMs is indeed associated to dimensionality of the data and thus movement complexity. However, in the group-analysis the number of PMs required to reach a certain level of explained variance might relate to the movement complexity, as well as to inter-individual differences (Figure 3). As such, care should be taken when interpreting explained variance results stemming from these separate methods.

In summary, this study aimed to assess the comparability between PCA outcomes determined from two separate measurement systems, from the same movement. To conclude, the results of the suggest good internal consistency in lower-order PMs (in fact, near perfect internal consistency in PM_1). The study also showed, that particularly in the group-level analysis, correlations can also be found between PMs of different order. This finding has important implications for applications of the PMs, particularly for the sensitivity of higher-order PM variables, PM-based measures of complexity and for the statistical treatment of PM-based results.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://osf.io/rz8qf/.

Ethics statement

The protocol of this study was reviewed and approved by the Department of Sport Science Ethics Review Board, University of Innsbruck. The participants provided their written informed consent to participate in this study.

Author contributions

SV and PF originally designed the study, SV, PF, and AS designed the data collection protocol and AS completed the measurements. SV, PF, and MM completed data analysis and wrote the first draft of the manuscript. IW and AS provided critical review and assistance in refining the manuscript. All authors helped finetune the final version of the manuscript and provided their consent for submission.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbioe.2022.1006670/full#supplementary-material

SUPPLEMENTARY FIGURE S1
Matrix $_{group}R$ of the correlation coefficients between $^{Vicon}_{group}PM_k$ and $^{Vicon}_{group}PM_k$. Correlations were determined after separating PCA results back into individual matrices, coefficients shown here represent the mean absolute correlation coefficients averaged over the entire subject group.

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Ningbo University, China
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Kazimierz Wielki University of Bydgoszcz, Poland

*CORRESPONDENCE
Rosa Angulo-Barroso
rosa.angulobarroso@csun.edu
Albert Busquets
albert.busquets@gencat.cat

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Children's strategies in drop-landing

Rosa Angulo-Barroso[1,2]*, Blai Ferrer-Uris[1], Júlia Jubany[3] and Albert Busquets[1]*

[1]Institut Nacional d'Educació Física de Catalunya (INEFC), Universitat de Barcelona (UB), Barcelona, Spain, [2]Department of Kinesiology, California State University, Northridge, CA, United States, [3]Faculty of Health Sciences at Manresa, Universitat de Vic – Universitat Central de Catalunya (UVic-UCC), Manresa, Spain

Introduction: Landing is a critical motor skill included in many activities performed in the natural environment by young children. Yet, landing is critically relevance to ensure proper stability and reduce injury. Furthermore, landing is an integral part of many fundamental motor skills which have been linked to greater physical activity, sport participation, and perceived competence in children. Our aim was to examine the drop-landing strategies of young children focusing on the lower extremity with a multi-variant approach.

Methods: Forty-four children divided into four age groups (G1:3–4.5 y, G2:4.5–6 y, G3:6–7.5 y, G4:7.5–9 y) performed 20 drop-land trials in four different conditions: predictable stationary landing, running to the left, to the right, and stay in place. Fifteen reflective markers, two force plates, and ten surface electromyography (sEMG) sensors were used to collect data. MANOVAs (Group x Condition) were conducted separately for the kinematic, kinetic, and sEMG variables.

Results: Only significant group effects were found (kinematic MANOVA $p = 0.039$, kinetic MANOVA $p = 0.007$, and sEMG MANOVA $p = 0.012$), suggesting that younger groups (G1, G2) differed to the older groups (G3, G4). G1 showed less knee flexion and slower ankle dorsi-flexion during the braking phase compared to G3, while G2 presented smaller ankle dorsi-flexion at the braking phase and smaller ankle range of motion than G3. Overall kinetic variables analysis showed a group difference but no group differences for any single kinetic variable alone was found. Regarding sEMG, G1 during the flight phase exhibited longer tibialis anterior and hamstrings activity than G3 and G3 & G4, respectively; and an earlier start of the hamstrings' impact burst than G4. In addition, distal to proximal control was primarily used by all groups to coordinate muscle activity (in response to impact) and joint motion (after impact).

Discussion: Perhaps a developmental critical point in landing performance exists at 4–5 years of age since G1 presented the largest differences among the groups. This suggests that to improve landing strategies could start around this age. Future studies should examine if playground environments that include equipment conducive to landing and practitioners in the kindergarten schools are adequate vehicles to empower this type of intervention.

KEYWORDS

kinematics, kinetics, muscle activity, coordination, landing, land-run, young children

Introduction

The acquisition of proficiency in fundamental motor skills (FMS) such as running or throwing has been recognized as a building block for greater physical activity, play, sport participation, and better perceived competence (Okely et al., 2001; Stodden et al., 2008; Barnett et al., 2009). Most children continue developing these FMS until age twelve, then they go on to refining them as developmental changes progress into adulthood (Barber-Westin et al., 2006). FMS have been classified as locomotor and object manipulation (Magill and Anderson, 2014), with landing not being included in this traditional classification despite its common use (Seefeldt, 1986; Zhao et al., 2021). Some authors consider landing as a stabilizing motor skill (Mckinley and Pedotti, 1992) but not a FMS because landing typically occurs after a drop from a height or a jump; in other words, landing is considered a subsequent part of FMS such as running, jumping, and hopping. Regardless of its classification, it is clear that FMS and stabilizing motor skills (including landing) are part of the natural course of physical growth and development. Therefore, targeting these skills during practice would better equip children with proper technique and enhance their future physical activity potential since active children are more likely to be active adults (Okely et al., 2001; Barnett et al., 2009). Although landing is a critical motor skill included in many daily, recreational, and sport activities and its development seems to be interconnected to FMS, research focusing on the development of landing as a motor skill is scarce.

In addition to the relevant role that proper landing may play in the development and physical activity participation of a child, adequate technique in landing is important to prevent potential injuries. Most young children enjoy going to the playground, whether in school or at a park, and practice several motor skills including landing. Playground typical equipment includes swings, slides, elevated platforms, and monkey bars among others. Landing effectively from these devices is fundamental to safe participation in many play activities such as jumping from an elevated platform or dropping from a swing or monkey bar. Unfortunately, most injuries occur during these conditions. In fact, Loder (2008) studied children's injuries in the playground and found that injuries owning to the monkey bars remained the same from 1991 to 2005 while those owning to slides or swings decreased. The authors suggested that prevention strategies to reduce number of fractures should be directed at monkey bar equipment and landing surfaces. Besides these contextual characteristics affecting landing performance, children must adapt their motor skills to their constantly changing body and maturing nervous system. The greatest incidence of sprains and ACL injuries occurs during adolescence while landing (DiStefano et al., 2015) and it could be related to poor or incorrect landing acquisition during childhood. Taking together all these data may indicate the need for early interventions to ensure better landing skills and yet studies examining the development of landing motor strategies from younger ages (kindergarten and elementary school years) are very scarce.

Research focused on the development of landing mainly compared children around 9–10 years old and adults considering different types of landing. These types can be grouped on (1) drop-land tasks, which entails hanging from a bar or taking off from an elevated platform and landing (Hinrichs et al., 1985; Larkin and Parker, 1998; McMillan et al., 2010; Kim and Lim, 2014; Christoforidou et al., 2017; Estevan et al., 2020; Schroeder et al., 2021; Koo et al., 2022; Moir et al., 2022), and (2) jump-land tasks, which entails jumping horizontally or upwards (off a box or not) and landing (Hass et al., 2003; Russell et al., 2007; Xu et al., 2020). Despite of the possible differences related to the task specificity, previous literature presented evidence that pre-pubescent children between 7 and 12 years are less efficient diminishing the rate loading (higher peak of forces and shorter time to these peaks and also to the end of the braking phase) (Larkin and Parker, 1998; McKay et al., 2005; Lazaridis et al., 2010) because of: (1) their anticipatory strategies rely mostly on their muscle activation with higher time of activation before impact (Christoforidou et al., 2017); (2) during the impact they increase the muscle co-activity of the knee muscles but not the ones related to the ankle dorsiflexion (Croce et al., 2004; Russell et al., 2007; Wild et al., 2009), and (3) after impact, they tend to present more proximal-distal control with more muscle co-activity and limited range of motion of the lower limb joints in the sagittal plane (Hinrichs et al., 1985; Larkin and Parker, 1998; Hass et al., 2003; Croce et al., 2004; Kim and Lim, 2014; DiStefano et al., 2015; Raffalt et al., 2017; Niespodziński et al., 2021). To our knowledge, only Jensen et al. (1994) studied younger children (3–4 years old) in comparison with adults suggesting that children coordinate joint actions similarly to adults during landings after a vertical jump but exhibited a poor control of the muscle strength to perform adequate joint displacement and/or velocities.

When observing children in the playground, one realizes that children's landing actions are usually followed by another task (running, for example). Furthermore, these tasks are typically initiated in response to the changing context, which sometimes cannot be predicted because of the variable behavior of other children in the same space requiring a change of the initial direction to avoid bumping into each other. It is often mentioned that an unanticipated change of direction is a high risk movement associated with ACL injuries (Fuerst et al., 2017; Whyte et al., 2018; Weir et al., 2019) because the limited time to respond to the stimulus could lead to suboptimal decision making and errors in coordination that can promote injuries (Swanik et al., 2007; Yom et al., 2019). It is also plausible that individuals use alternative motor strategies to prepare landings with unanticipated response (Yom et al., 2019), injuries could appear when the alternative motor strategy is not good enough or is not properly used before starting movements following landing. The effects of an unanticipated change of direction movement to run from a double-leg landing are not well studied. Yom et al. (2019) reported no significant differences in vertical ground reaction forces and in hip, knee and ankle maximum flexion values when comparing adults performing anticipated or unanticipated change of directions to run after double-leg landings from a monkey bar. There is some research in children focusing on the combination of landing when it is followed by another predictable task (Croce et al., 2004; McKay et al., 2005; Swartz et al., 2005; Lazaridis et al., 2010; DiStefano et al., 2015; Niespodziński et al., 2021) but only, to our knowledge, Rosales et al. (2018) studied younger children (with typical development, TD, and with autism spectrum disorder, ASD) drop-landing followed by anticipated or unanticipated running conditions. The authors reported similar results in kinematics and muscle activity across conditions while more mature landing strategies were shown by TD with longer bursts of muscle activation during impact and shorter time to maximum knee and hip flexion during the braking phase.

Given the scarcity of evidence and the fact that effective motor skill performance like landing depends on previous early motor learning (Santello and Mcdonagh, 1998; Santello, 2005; Barber-Westin et al., 2006), it seemed reasonable to focus our research on the earlier years (3–9 years) which, at the same time, could provide new insights about the motor control development of landing. There are endless possibilities for the combinations of the aforementioned tasks. The self-initiate drop-land task seemed to be the simpler of all, and therefore most suitable to be studied in very young children. However, because landing rarely occurs in a vacuum, landing tasks that require to be followed by an unexpected or expected action are also relevant to understand overall landing strategies. The purpose of this study was to examine the drop-landing strategies of young children focusing on the lower extremity with a multi-variant approach (i.e., kinematic, kinetic, and muscle activity variables). We hypothesized that youngest children compared to older children will show a less efficient landing with (1) lower and shorter rate of loading due to impact; (2) less muscle specific pre-activation before impact but more co-contraction throughout the landing; (3) less flexion in the hips, knees, and ankles (dorsiflexion) during the landing; and (4) more use of proximal-distal sequences to coordinate motion and muscle activation.

Methods

Participants

Forty-four children (16 girls, 28 boys aged 3.1–8.9 y) participated in the study voluntarily (Table 1). The participants had no known history of lower extremity injuries. The participants were divided into four age groups: G1 (aged 3–4.5 y), G2 (aged 4.5–6 y), G3 (aged 6–7.5 y), and G4 (7.5–9 y). Subjects were not specialized in vertical jumps through training (e.g., volleyball, gymnastics) but they could participate in extracurricular activities. Children were recruited from schools in the San Fernando Valley and service learning programs at the university. Parents provided informed consent to participate in the study. The Institutional Review Board at California State University, Northridge, approved the study.

Procedure

The participants and their caregivers came to the motor development laboratory once to carry out the whole experimental procedure (Figure 1). Participants were asked to change into compression shorts and a tank top and to remove their shoes. At the start of the session, anthropometric data were obtained, including: height, weight, leg length, and standing vertical reach. In addition, participant's maximal vertical jump was also measured. Next, a trained laboratory member placed 10 wireless surface electromyography (sEMG) devices (Delsys Incorporated, Natick, MA, USA) on participants after their skin was cleaned and abraded with an alcohol solution. sEMG was placed and recorded on both sides of the body for gastrocnemius (G), tibialis anterior (T), quadriceps (Q), hamstrings (H), and erector spinae (E), following the SENIAM guidelines (Hermens et al., 1999) (Figure 2A). In addition, 15 reflective markers were placed on the following anatomical landmarks: center of the forehead, base of the skull, cervical vertebrae 7 (C7), and on both sides for the acromion, lateral epicondyle of the humerus, greater trochanter, lateral side of the knee, lateral malleolus, and the fifth metatarsal (Figure 2A). Afterwards, participants performed the landing task consisting on landing from a monkey bar (Figure 2B). The individual bar height was determined following Rosales et al. (2018). For safety reasons, the individual bar height was tested for each child using few assisted drops before data collection. One of the researchers lifted the participants helping them to steadily hang on the bar at the start of each trial. Participants performed 20 trials of the landing task, where they were asked to land onto 2 force plates (Kistler, Winterthur, Switzerland) (Figure 2B); one foot on each force plate. Trials were executed in four different landing conditions. On one of the conditions, participants were totally aware of what they had to do upon landing (predictable response, P), while for the other three conditions participants had to respond to a light cue (stop light, light at their left, or light at their right side) lit by the force plates upon initial contact when landing (unpredictable response, U). Therefore, the four conditions were: a predictable response condition were participants had to land on their feet and remain stable and stationary (PS); an unpredictable response condition were participants had to land on their feet and remain stable and

TABLE 1 General characteristics of the sample.

	Group 1 (*N* = 11; 3 ♀)		Group 2 (*N* = 10; 4 ♀)		Group 3 (*N* = 10; 1 ♀)		Group 4 (*N* = 13; 9 ♀)	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Age (years)	3.95	0.49	5.31	0.33	6.70	0.33	8.42	0.32
Height (cm)	102.51	6.91	112.93	4.58	124.30	7.03	130.45	5.12
Weight (kg)	16.18	2.45	20.06	3.23	25.69	4.78	27.49	4.10
Leg lenght (cm)	42.44	4.07	50.26	2.63	55.95	5.36	60.07	3.05
Reach height (cm)	124.76	9.34	141.92	5.77	157.72	11.37	167.54	7.93
Maximum vertical jump (cm)	133.59	12.00	158.77	6.02	179.32	15.38	191.79	11.12
Bar height used (cm)	145.59	15.55	168.40	6.36	189.52	15.76	201.27	10.15

♀ = female birth sex.

stationary (US); and two unpredictable response conditions were participants had to land and then run toward the light located to their left (UL) or right (UR) side. Each participant performed 5 trials of each condition, always starting with 5 non-randomized PS trials and, afterwards, performing the following 15 trials of the rest of the conditions presented in random order. For the PS and US trials, participants were instructed to "land and remain as still as possible for 5 s (if you see the stop light, for US)", while for the UL and UR trials, participants were instructed to "land and run as fast as possible toward the lit light". When a trial was considered not valid because participants dropped before the Go signal or because participants landed with both feet touching one force plate, an additional trial of that condition was performed. At least 2 min rests were provided every 5-trial set.

Data collection

Kinematic data were captured at 100 Hz using a ten-camera Qualisys 3D motion analysis system (Qualysis AB, Göteborg, Sweden) (Figure 2B). Prior to data collection, the motion analysis system was calibrated according to the manufacturer's recommendations. The two force plates, embedded into the floor, were employed to capture ground reaction forces at a sampling frequency of 2,000 Hz. The muscle activity was recorded with 10 wireless Trigno Delsys sEMG sensors with the following characteristics: sampling frequency 1926 Hz, CMRR >110 dB at 50/60 Hz, gain: 1.000, bandwidth: 10–500 Hz, and bipolar surface Ag/AgCl disc electrodes (diameter: 0.8 cm, inter-electrode distance: 2 cm). Force plate and sEMG data were collected and synchronized along with the 3D motion analysis system through the specialized plug-ins and hardware of the Qualisys motion analysis system (Figure 2C).

Data analysis

The objective of a successful land is to absorb the kinetic energy of the body, while refrain the lower extremity from collapsing under the force and to maintain balance and stability (Mckinley and Pedotti, 1992; Haywood and Getchell, 2014; Christoforidou et al., 2017). Most of the previous studies have divided landing in: (a) flight phase, which usually starts when the center of mass begin to descend and ends just prior to touch-down (also called impact); (b) pre-impact, a time window included in the flight phase typically defined from 100 ms prior to impact; (c) impact, as the instant of time of touch-down; (d) post-impact, a time window typically defined from impact to 100 ms later; and (e) braking phase, which starts the time from impact to maximum knee flexion and includes the post-impact window. Each of these divisions contributes differently to better understand changes of the motor strategies to a more

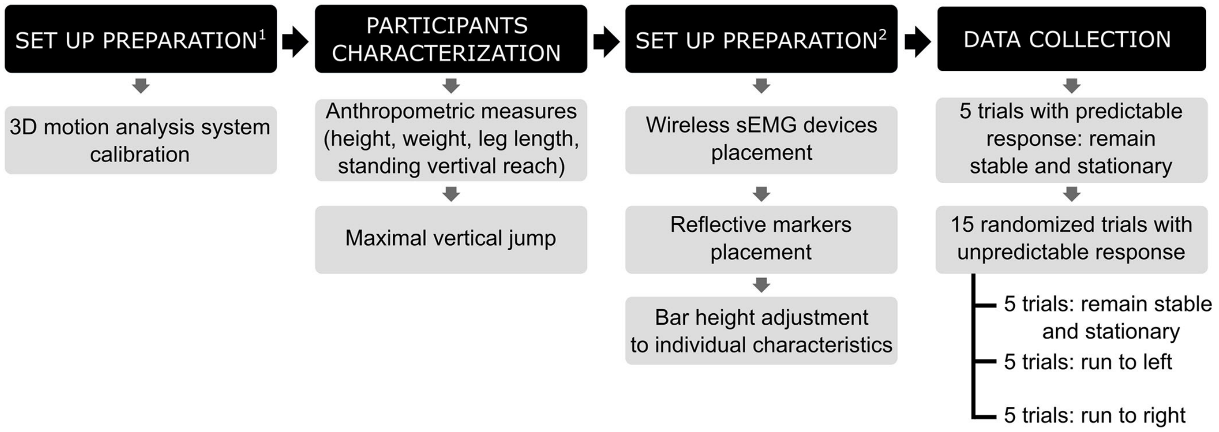

FIGURE 1
Flow chart of the experimental procedure.

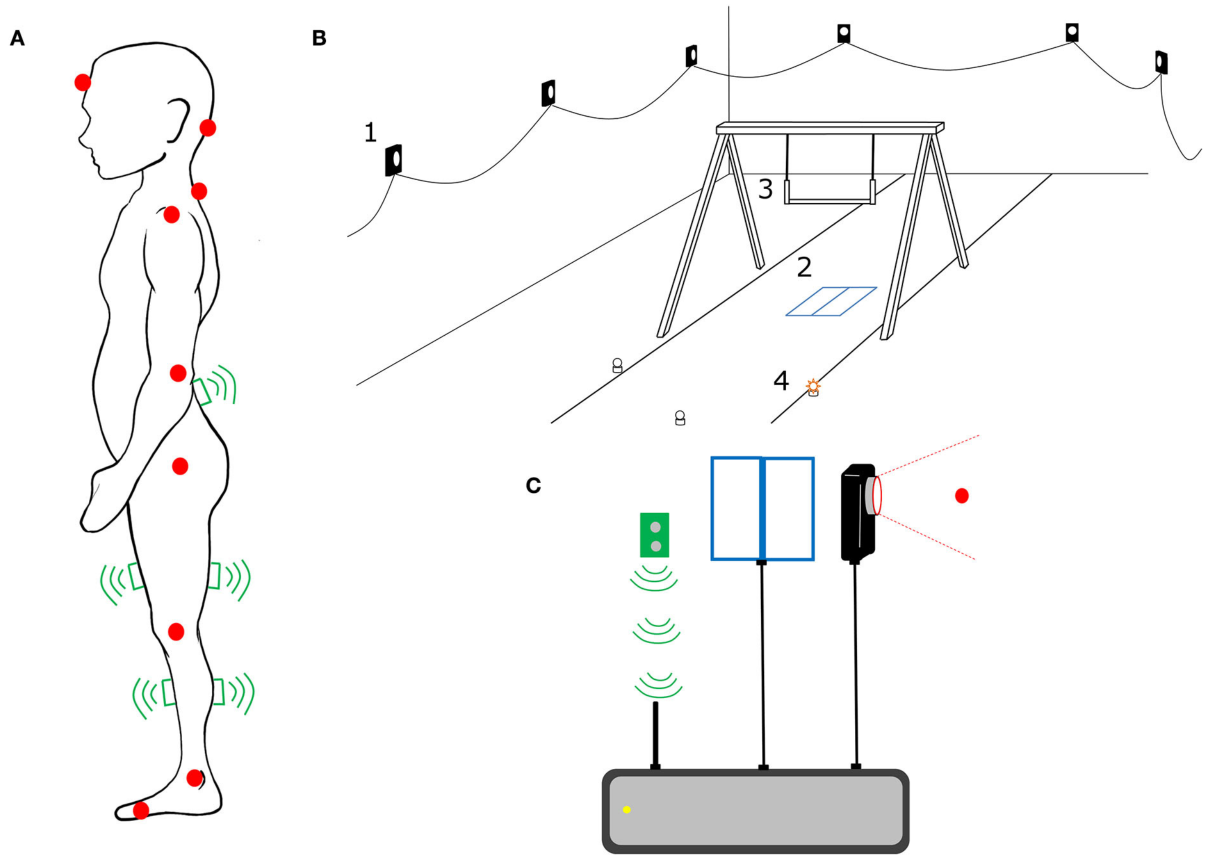

FIGURE 2
Schematic illustration of the experimental setup: **(A)** sketch of the reflective markers and the wireless surface electromyography (sEMG) devices disposition on participants; **(B)** infrared cameras to capture 3D motion data (2), two force plates (2), adjustable high bar (3), and light cues to respond during unpredictable response trials (4); and **(C)** flow chart of the 3D motion data from sEMG, force plate, and infrared cameras data synchronized through the specialized plug-ins and hardware of the Qualisys motion analysis system.

mature landing execution. For example, the muscle activation before impact is critical to study anticipatory actions to face the impact, while the periods after impact allow us to focus on how muscle activation patterns and multi-joint movement coordination reduce the rates of loading until equilibrium is reached (Mckinley and Pedotti, 1992; Liebermann, 2008; McNitt-Gray, 2016).

Data analysis was performed with custom made Python scripts (Python Software Foundation) and in Labwindows CVI2010 (National Instruments, Austin, TX, USA) for the Kinematics, force plates, and sEMG data. A modified algorithm for detecting sEMG onset/offset following Jubany and Angulo-Barroso (2016) was also used for the sEMG data analysis.

Kinematics data were filtered with a recursive low-pass 4th-order Butterworth filter with a cut-off frequency of 6 Hz. From filtered kinematics data, vertical velocities of the C7, right elbow, and left elbow markers were computed. In addition, bilateral hip, knee, and ankle angular positions and angular velocities were also calculated. The impact event identified though the analysis of the force plates data (see impact event definition in the next paragraph) was set as zero on the timeline. Two additional events were identified though the kinematics data: the let-go event and the braking offset event (BO). Let-go was characterized as the latest time-point where a 2% of the maximum negative vertical velocity was obtained for the C7, right elbow, or left elbow markers at the start of their descending trajectory after the participants released the bar. The BO was defined as the latest time-point where the maximum right or left knee flexion (i.e., minimum knee angle) was obtained within a time window of a maximum of 350 ms after the impact event. These three events were used to define the flight phase (FP, from let-go event to impact event) and the braking phase (BP, from impact event to BO) which were used in the subsequent analyses. See Figure 3 for a graphical example where events and phases are identified.

Raw vertical force plate data were used to identify the following events. Impact (Imp) was defined as the earliest time-point were one of the two plates reached a vertical force of 10 N or greater. Afterwards, two peaks were identified in the vertical force registry of each plate: first peak after impact event (P1) and maximum peak force after the first peak (P2).

Surface EMG was filtered using a recursive 4th-order band-pass Butterworth filter with 20–500 Hz cut-off frequencies. The impact event (Imp) defined through force plates data was used to label as time 0 and was transferred to all sEMG channels. The sEMG baseline signal for each muscle was taken as the lowest mean value (200 ms window) found across all valid trials for each participant when the participant was hanging from the bar (i.e., before the let-go event defined using kinematic data). Burst onsets and offsets were detected during the 300 ms prior and 500 ms after to impact event. This detection involved two steps: (1) an initial detection process identifying potential burst segments; and (2) a final onset and offset definition of the true bursts (see Figure 4 for more in depth explanation).

After individual muscle bursts were identified, two co-contraction burst pairs were defined; one between the tibialis anterior (T) and gastrocnemius (G) and the other between quadriceps (Q) and hamstrings (H). A co-contraction burst was identified when simultaneous activity bursts were previously identified for both muscles. For sEMG variables only, and in addition to the already defined flight and braking phases, two 100 ms time-windows were defined around impact: pre-impact (−100 to 0 ms) and post-impact (0 to +100 ms).

Variables

Kinematic variables and flexion timing pattern

Kinematic variables were computed during the BP for each valid trial. They were calculated as the mean of the values extracted from the right and left side joint angle (full extension 0°) and angular velocities data: maximum hip and knee flexion and ankle dorsi-flexion angle defined as the maximum angle (θ_{Hip_max}, θ_{Kne_max}, and θ_{Ank_max}, respectively); range of motion defined as the difference between the maximum and minimum joint angles ($\theta_{Hip\_max-min}$, $\theta_{Kne\_max-min}$, and $\theta_{Ank\_max-min}$); time of maximum flexion angle for the hip ($t\theta_{Hip\_max}$), knee ($t\theta_{Kne\_max}$) and ankle ($t\theta_{Ank\_max}$); maximum flexion velocity for the hip (ω_{Hip_max}), knee (ω_{Kne_max}), and ankle (ω_{Ank_max}). Additionally, the time of the maximum flexion angles ($t\theta_{Hip\_max}$, $t\theta_{Kne\_max}$, and $t\theta_{Ank\_max}$) were utilized to characterize the joint flexion timing pattern of the lower limb. Patterns where typified as: Distal (Dis_kinPattern) when the ankle dorsiflexion preceded the knee and hip maximum flexions (distal to proximal flexion), Proximal (Pro_kinPattern) when the hip maximum flexion preceded the knee and ankle maximum flexion (proximal to distal flexion), Mixed (Mix_kinPattern) when in the sequence the maximum knee flexion is the last to occur (e.g., ankle < hip < knee), and Other (Oth_kinPattern) for any other possible combinations (e.g., ankle = Knee < hip).

Kinetic variables

Kinetic variables were computed using vertical force data and after defining Imp, P1, P2, and BO (the latter defined through the kinematics data) on each side (right and left). All variables extracted from the force data registry characterized the BP of each valid trial and they were calculated as the mean of both sides and body weight was used to normalize force values and calculations from them. The following dependent variables were obtained: force value at peak one (F_{P1}), force value at peak two (F_{P2}), time of peak two (tF_{P2}), impulse from impact to peak two (I_{Imp-P2}), and impulse from impact to braking offset (I_{Imp-BO}).

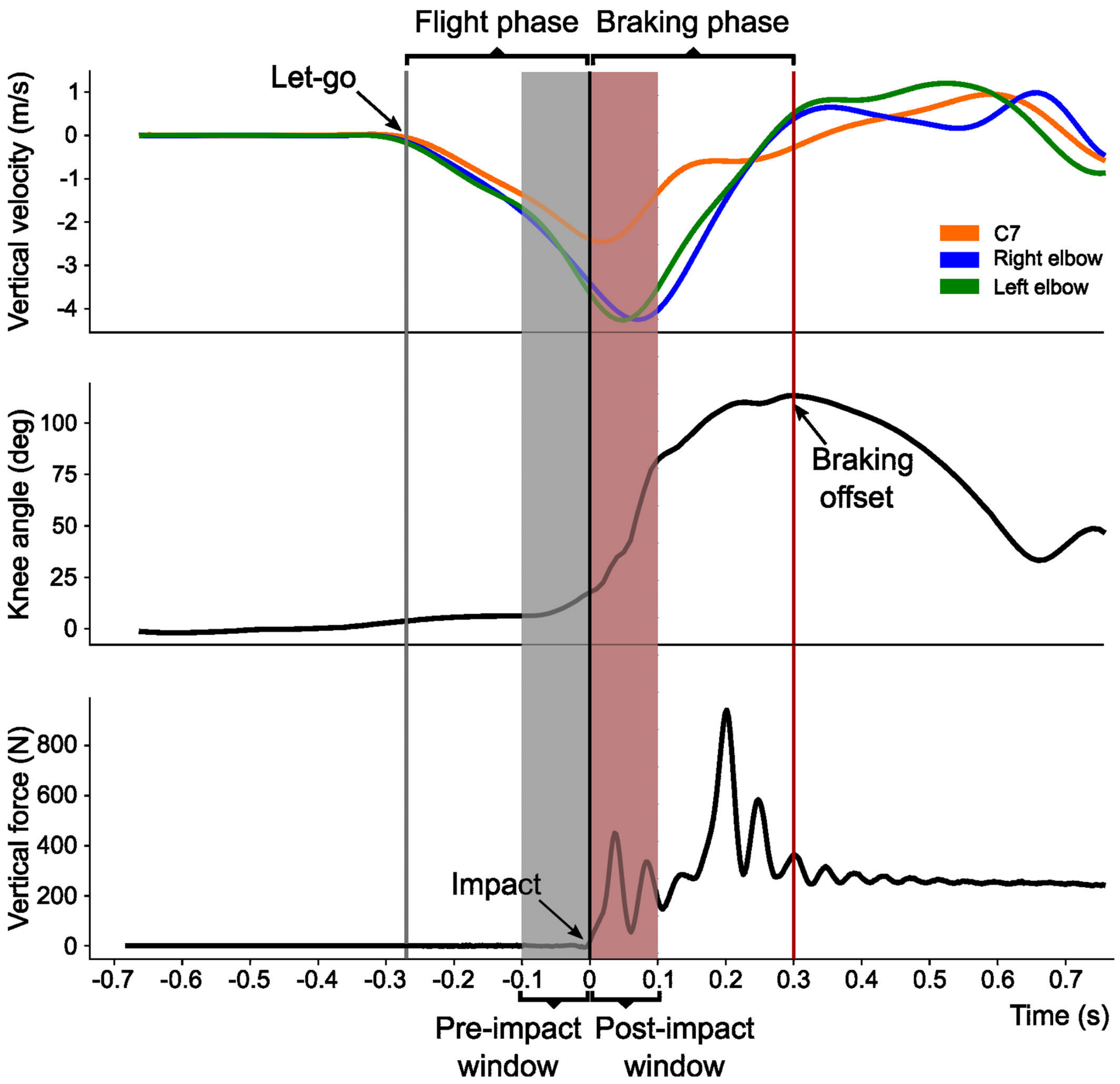

FIGURE 3
Example of kinematics and kinetics data with identification of the main events, phases, and windows utilized for the data analysis. Three events were characterized: (a) Let-go event, marking the instant of the bar release and defined from the vertical velocity of the C7, Right elbow, and Left elbow markers (gray vertical line); (b) Braking offset event, representing the end of the impact absorption and characterized through the knee angular position (red vertical line); and (c) Impact event, indicating the initial contact with the floor and identified using the vertical force data from the force plates (black vertical line). Two phases were defined from these events: the Flight phase, comprised between the Let-go and Impact events; and the Braking phase, comprised between the Impact and Braking offset events. In addition, a Pre-impact (gray shadowed area) and Post-impact (red shadowed area) 100 ms windows were defined around the Impact event.

Muscle activity variables and muscle patterns response to the impact

Regarding the sEMG variables, percentage of active time (muscle % activity = time of burst activity within phase or window/total phase duration * 100) of each muscle (E, G, H, Q, and T) was computed for the FP and the pre-impact window (Pre). In addition, % activity of co-contracting muscles pairs (T-G and Q-H) was computed for the post-impact window (Pos) and the BP (pair % co-contracting activity = time of co-contraction activity within phase or window/total phase duration * 100). Means of both sides (right and left) for each valid trial were calculated to define the muscle activity ($E\_\%_{FP}$, $E\_\%_{Pre}$, $G\_\%_{FP}$, $G\_\%_{Pre}$, $H\_\%_{FP}$, $H\_\%_{Pre}$, $Q\_\%_{FP}$, $Q\_\%_{Pre}$, $T\_\%_{FP}$, $T\_\%_{Pre}$,) and the co-contraction activity variables

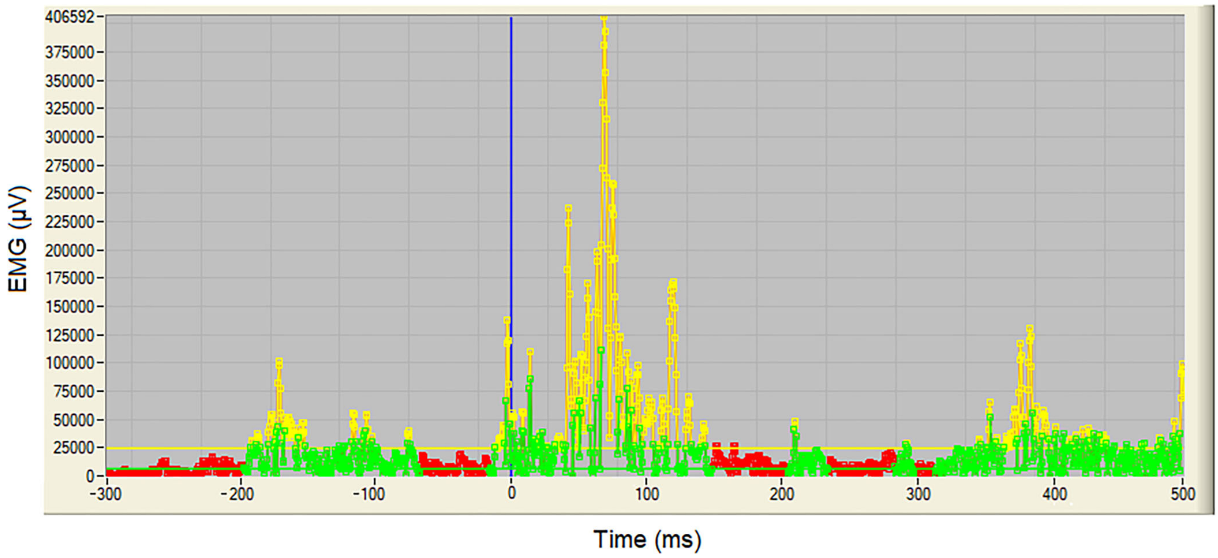

FIGURE 4
Example of a sEMG burst detection procedure with 300 ms prior to impact and 500 ms after impact. This detection involved two steps: (1) an initial detection identifying the continuous data that were higher than the mean plus 8 SD of the baseline values for at least 1.55 ms (3 data points) which yielded a temporary definition of the burst segment duration and its corresponding temporary onset and offset burst points (in yellow); and (2) a final onset and offset definition of the burst where burst onset and offset were redefined calculating the mean of a backwards or forward, respectively, running window (4.15 ms = 8 data points) around the temporary burst points defined in the first step and establishing the earliest or latest data point, respectively, at which the window mean was higher than the baseline mean plus 1 SD (in green). All data between the final burst onset and the final burst offset were considered as one sEMG burst. The rest of the data points were considered to be at baseline level (in red). The vertical blue line indicates the impact event (Imp).

(Q-H_$\%_{BP}$, Q-H_$\%_{Pos}$, T-G_$\%_{BP}$, T-G_$\%_{Pos}$). On the other hand, anticipatory or reactive muscle activity to impact was characterized identifying the occurrence of impact and post-impact bursts. Impact bursts were defined as those muscle bursts that started at least 40 ms before impact and lasted, at least, 40 ms after impact. Post-impact bursts were defined as the first activity burst that started 40 ms after the impact or later and that lasted 80 ms or more. Impact bursts were used to compute the percentage of occurrence of an impact activity burst ($\%B_{Imp}$) along the five trials of each condition (E_$\%B_{Imp}$, G_$\%B_{Imp}$, H_$\%B_{Imp}$, Q_$\%B_{Imp}$, and T_$\%B_{Imp}$). The start-time of those impact bursts (tB_{Imp}) was also obtained for each trial and muscle. The mean between the tB_{Imp} of both sides (right and left) in each trial were used to calculate E_tB_{Imp}, G_tB_{Imp}, H_tB_{Imp}, Q_tB_{Imp}, and T_tB_{Imp}. Finally, the start-times of the impact and post impact bursts were used to examine which first two muscles initiated their activation in response to the impact. If an impact burst was not found for a muscle, the post-impact burst was used instead. Based on the first two activated muscles, six muscle activation onset patterns where typified: distal (Dis_EMGPattern) when G and T were the two first muscles activated; proximal (Pro_EMGPattern) when H and Q were the two first muscles activated; mixed anterior (Mix_{Ante}_EMGPattern) when Q and T were the two first muscles activated; mixed posterior (Mix_{Post}_EMGPattern) when G and H were the two first muscles activated; and mixed crossed (Mix_{Cros}_EMGPattern) when H and T or G and Q are the two first muscles activated, and other (Oth_EMGPattern) any other possible combinations when E was activated.

Statistical analysis

General lineal mixed model with repeated measures in each variable were conducted to assess the trial effect, except for the percentage of impact activity burst occurrence variables (E_$\%B_{Imp}$, G_$\%B_{Imp}$, H_$\%B_{Imp}$, Q_$\%B_{Imp}$, and T_$\%B_{Imp}$) which were calculated using the five trials of each condition. General lineal mixed model were applied because non-normal distribution of data was detected with Shapiro–Wilks tests and missing measurements appeared in some participants' trials (Bolker et al., 2009; Harrison et al., 2018). Two models were calculated, the first where children were included as a random factor while trial, condition, and age group were introduced as fixed factors. In the second model, no random factors were included. The model without random factors demonstrated better fit after checking the Bayesian Information Criteria. This model showed no significant trial effect in 59 out of 66 variables. Given that mostly no significance trial effects were found, individual means for each variable were calculated across the five trials for each condition (P, US, UL, UR).

Five MANOVAs with repeated measures (4 Age groups x 4 Conditions) were used to evaluate age and condition effects and interactions on kinematics, kinetics, flight phase sEMG, braking phase sEMG, and burst occurrence variables. Due to different sample size of the impact bursts start-time of each muscle, age-group and condition effects were assessed using ANOVAs with repeated measures (4 Age groups x 4 Conditions) for each variable (E_tB_{Imp}, G_tB_{Imp}, H_tB_{Imp}, Q_tB_{Imp}, and T_tB_{Imp}). Potential Type I error was controlled adjusting p values from univariate ANOVAs conducting Bonferroni's correction. Also, sphericity-corrected values by Greenhouse-Geisser were obtained when appropriate. Finally, pairwise comparisons with Bonferroni correction were used to establish differences between age-groups and conditions. The effect size was measured by partial eta squared (small effect size: $\eta^2 p \leq 0.010$; medium effect size: $\eta^2 p \leq 0.059$; large effect size: $\eta^2 p \leq 0.138$).

Chi-square contingency tables were computed to evaluate the effect of the age and the conditions in the joint flexion timing pattern and muscle activation onset pattern responses to the impact. Bonferroni correction was applied to adjust z test calculation for each row.

Statistical significance of all tests was set at the $p < 0.05$ level and only statistically significant results were reported. All statistical tests were performed with SPSS PASW Statistics 21 software (SPSS, Inc., Chicago, IL, USA).

Results

Kinematics, kinetics, flight phase sEMG, braking phase sEMG, and burst occurrence variables were compared by MANOVAs with age-group as a between factor and the four task conditions as within factor. Results from these MANOVAs showed significant Group main effects on the kinematics, the kinetics, and the flight phase sEMG variables (Table 2). No significant Condition main effects or Group x Condition interactions were found. Subsequent one-way ANOVAs from MANOVAs that presented Group main effects revealed significant differences in four kinematic variables (θ_{Ank_max}, $\theta_{Kne\_max-min}$, $\theta_{Ank\_max-min}$, and ω_{Ank_max}) and three flight phase sEMG variables ($G\_\%_{FP}$, $H\_\%_{FP}$, and $T\_\%_{FP}$) (Table 2). On the other hand, ANOVAs conducted on muscle impact bursts start-time showed significant Group and Condition main effects on G_tB_{Imp} and H_tB_{Imp} but a significant interaction only was found in H_tB_{Imp} (Table 3). Finally, joint flexion timing pattern and muscle activation onset pattern responses to the impact yielded statistically significant differences by group when chi-square contingency tables were computed (Tables 4, 5).

TABLE 2 Significant main effects and Group x Condition interactions: MANOVAs in bold-*italicized* and subsequent ANOVAs significant results.

Variable group	Variable name	Main effect or interaction	F	df	p	$\eta^2 p$	Power	Pairwise comparisons	Homogeneous subsets 1	Homogeneous subsets 2
Kinematics		**Group**	***1.598***	***3,39***	**0.039**	***0.39***	***0.981***			
	θ_{Ank_max}	Group	3.280	3,39		0.201 0.031	0.706	G2 > G3	G1, G2, G4	G1,G3, G4
	$\theta_{Kne\_max-min}$	Group	3.339	3,39	0.029	0.204	0.715	G1 < G3	G1, G2, G4	G1,G3, G4
	$\theta_{Ank\_max-min}$	Group	3.986	3,39	0.014	0.235	0.796	G2 < G3	G1, G2, G4	G3, G4
	ω_{Ank_max}	Group	3.38	3,39	0.028	0.206	0.721	G1 > G3	G1, G2, G4	G2, G3, G4
Kinetics		**Group**	***2.306***	***3,39***	**0.007**	***0.253***	***0.97***			
sEMG: % activation		**Group**	***1.873***	***3,39***	**0.012**	***0.369***	***0.990***			
	$G\_\%_{FP}$	Group	3.173	3,39	0.035	0.196	0.690	-	G1, G2, G3, G4	
	$H\_\%_{FP}$	Group	4.973	3,39	0.005	0.277	0.884	G1 > G3, G4	G1, G2	G2, G3, G4
	$T\_\%_{FP}$	Group	4.017	3,39	0.014	0.236	0.800	G1 > G4	G1, G2, G3	G2, G3, G4

θ_{Ank_max}, ankle maximum angle (i.e., maximum flexion); $\theta_{Kne\_max-min}$, knee flexion range of motion; $\theta_{Ank\_max-min}$, ankle dorsi-flexion range of motion; θ_{Ank_min}, ankle maximum angular velocity (i.e., maximum flexion velocity); G_%FP, Gastrocnemius percentage of activation during the flight phase; H_%FP, Hamstrings percentage of activation during the flight phase; T_%FP, Tibialis anterior percentage of activation during the flight phase; G1, group 1 (aged 3-4.5 years); G2, group 2 (aged 4.5-6 years); G3, group 3 (aged 6-7.5 years); G4, group 4 (aged 7.5-9 years).

TABLE 3 Significant main effects and Group x Condition interactions ANOVAs for sEMG burst variables.

Variable	Main effect or interaction	*F*	*df*	*p*	η^2p	Power	Pairwise comparisons
G_tB_{Imp}	Group	4.516	3,39	0.046	0.184	0.651	-
	Condition	2.926	3,39	0.005	0.104	0.874	PS < UR
H_tB_{Imp}	Group	3.157	3,39	0.035	0.195	0.688	G1 < G4
	Condition	5.582	3,39	0.003	0.125	0.898	PS < UL
	Group x Condition	2.569	3,39	0.016	0.165	0.881	US: G1 < G3, G4
							G3: PS < UL, UR, US

G_tB_{Imp}, start-time of the gastrocnemius impact burst; H_tB_{Imp}, start-time of the hamstrings impact burst; G1, group 1(aged 3–4.5 years); G2, group 2 (aged 4.5–6 years); G3, group 3 (aged 6–7.5 years); G4, group 4 (aged 7.5–9 years); PS, predictable landing response condition were participants had to land on their feet and remain stable and stationary; UL, unpredictable landing response condition were participants had to land on their feet and then run toward the light located to their left; UR, unpredictable landing response condition were participants had to land on their feet and then run toward the light located to their right; US, unpredictable landing response condition were participants had to land on their feet and remain stable and stationary.

TABLE 4 Chi square contingency table for joint flexion timing pattern variables.

Variable	Group	Dis_kinPattern *n (%)*	Pro_kinPattern *n (%)*	Mix_kinPattern *n (%)*	Oth_kinPattern *n (%)*	χ^2	*p*
Flexion timing patterns						47.24	<0.001
	G1	167 (75.2)	3 (1.4)	16 (7.2)	36 (16.2)		
	G2	157 (78.5)	2 (1.0)	25 (12.5)	16 (8.0)		
	G3	131 (65.8)*	3 (1.5)	42 (21.1)*	23 (11.6)		
	G4	224 (85.5)*	1 (0.4)	12 (4.6)*	25 (9.5)		

Dis_kinPattern, the ankle dorsiflexion preceded the knee and hip maximum flexions (distal to proximal flexion); Pro_kinPattern, the hip maximum flexion preceded the knee and ankle maximum flexion (proximal to distal flexion); Mix_kinPattern, when in the sequence the maximum knee flexion is the last to occur; Oth_kinPattern, other possible combinations; G1, group 1 (aged 3-4.5 years); G2, group 2 (aged 4.5-6 years); G3, group 3 (aged 6-7.5 years); G4, group 4 (aged 7.5-9 years).
*Indicates significant *post-hoc* result after Bonferroni correction.

Kinematic variables and flexion timing pattern

ANOVAs and their *post-hoc* showed differences between the third age group (G3) and the younger groups (G1 and G2), especially in the ankle motion variables (Table 2 and Figure 5). Concretely, the G3 performed larger ankle dorsi-flexion range of motion ($\theta_{Ank\_max-min}$) compared to G2 by achieving lower values of maximum ankle dorsi-flexion (θ_{Ank_max}). On the other hand, the youngest group (G1) performed the ankle dorsi-flexion range slower and flexed less the knee than G3. The differences presented and the homogeneous subsets created statistically by the MANOVA (Table 2) indicated that younger groups (G1, G2) performed drop-landings similarly to each other, but differently to the older groups (G3 and G4) which shared similarities but to a lesser extent.

Regarding the joint flexion timing pattern, all groups performed the drop-landings mainly with a distal sequence (Dis_kinPattern), specially the oldest group (G4) who showed the highest frequency (Table 4). Interestingly, G3 showed the lowest frequency using the distal sequence (Dis_kinPattern) while they executed the mixed pattern (Mix_kinPattern) more often (Figure 5).

Kinetic variables

Despite MANOVA results showed significant group main effect in the kinetic variables, no significant differences were found between groups when subsequent ANOVAs were conducted (Figure 6).

Muscle activity variables and muscle patterns response to the impact

ANOVAs and the *post-hoc* conducted on flight phase sEMG variables showed that the youngest group (G1) activated for more of the FP their hamstrings ($H\_\%_{FP}$) than the older groups (G3 and G4) and their tiabialis anterior ($T\_\%_{FP}$) than G4 (Table 2 and Figure 7). No pairwise differences were shown by the *post-hoc* analyses for the gastrocnemius percentage of activation during flight ($G\_\%_{FP}$) although a group main effect was found by the ANOVA (Table 2 and Figure 7).

Regarding the muscle impact bursts start-time, ANOVAs yielded significant differences between groups for the gastrocnemius and hamstrings but *post-hoc* comparisons only showed an earlier hamstring burst performance by younger

TABLE 5 Chi square contingency table for muscle patterns in response to the impact event.

Variable	Group	Dis_EMG Pattern *n (%)*	Pro_EMG Pattern *n (%)*	Mix_{Ante}_EMG Pattern *n (%)*	Mix_{Post}_EMG Pattern *n (%)*	Mix_{Cros}_EMG Pattern *n (%)*	Oth_EMG Pattern *n (%)*	χ^2	*p*
Muscle patterns response to impact								119.02	<0.001
	G1	96 (43.2)	0 (0.0)	8 (3.6)	53 (23.9)*	51 (23.0)*	14 (6.3)		
	G2	59 (29.5)*	3 (1.5)	34 (17.0)*	12 (6.0)*	69 (34.5)	23 (11.5)		
	G3	93 (46.7)	1 (0.5)	10 (5.0)	17 (8.5)	70 (35.2)	8 (4.0)		
	G4	103 (39.3)	2 (0.8)	11 (4.2)	41 (15.6)	88 (33.6)	17 (6.5)		

Dis_EMGPattern, gastrocnemius and tibialis anterior were the two first muscles activated; Pro_kinPattern, hamstrings and quadriceps were the two first muscles activated; Mix_{Ante}_EMGPattern, quadriceps and tibialis anterior were the two first muscles activated; Mix_{Post}_EMGPattern, gastrocnemius and hamstrings were the two first muscles activated; Mix_{Cros}_EMGPattern, hamstrings and tibialis anterior or gastrocnemius and quadriceps are the two first muscles activated; Oth_EMGPattern, other possible combinations when erector spinae was activated; G1, group 1 (aged 3-4.5 years); G2, group 2 (aged 4.5-6 years); G3, group 3 (aged 6-7.5 years); G4, group 4 (aged 7.5-9 years).
*Indicates significant post-hoc result after Bonferroni correction.

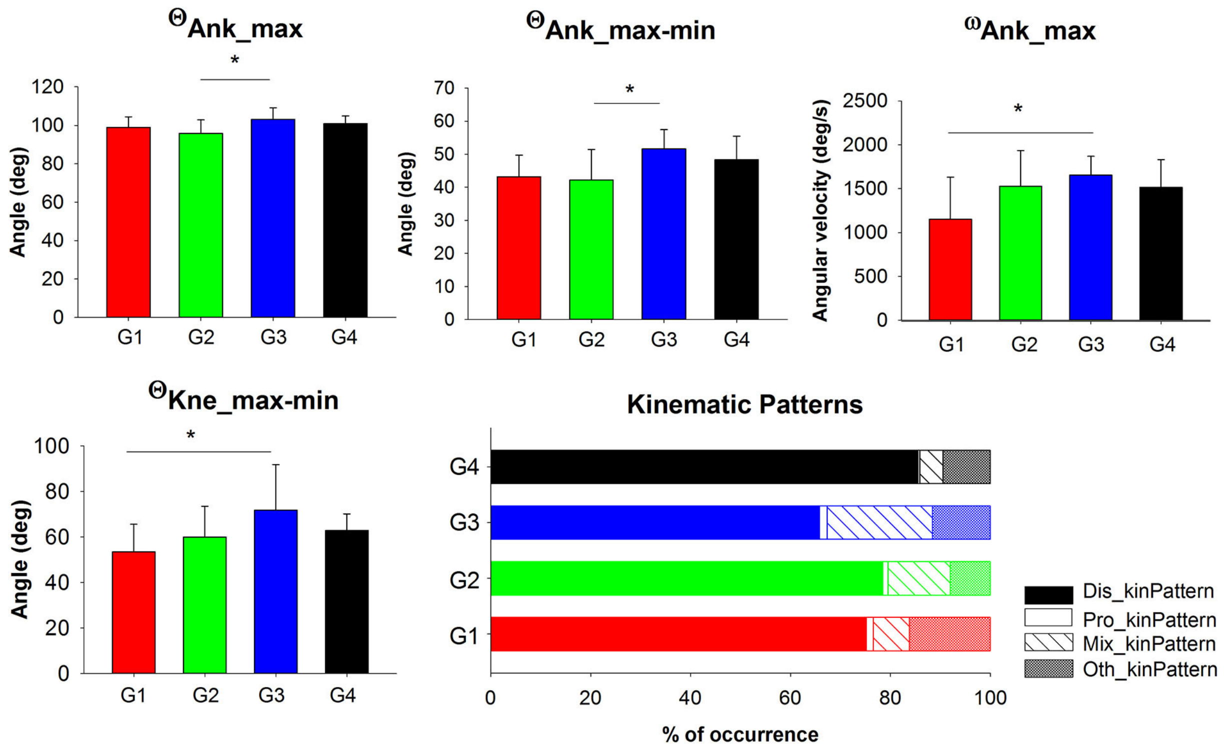

FIGURE 5
Significant Group main effects of kinematic variables and occurrence of the kinematic patterns. Mean and standard deviations of the kinematic variables and percentage of occurrences of the kinematic patterns were plotted by group. G1, group 1 (aged 3–4.5 years); G2, group 2 (aged 4.5–6 years); G3, group 3 (aged 6–7.5 years); G4, group 4 (aged 7.5–9 years); θ_{Ank_max}, ankle maximum angle (i.e., maximum flexion); $\theta_{Kne\_max-min}$, knee flexion range of motion; $\theta_{Ank\_max-min}$, ankle dorsi-flexion range of motion; ω_{Ank_max}, ankle maximum angular velocity (i.e., maximum flexion velocity); Dis_kinPattern, the ankle dorsiflexion preceded the knee and hip maximum flexions (distal to proximal flexion); Pro_kinPattern, the hip maximum flexion preceded the knee and ankle maximum flexion (proximal to distal flexion); Mix_kinPattern, when in the sequence the maximum knee flexion is the last to occur; Oth_kinPattern, other possible combinations. Asterisks (*) represent significant differences in the *post-hoc* analyses.

group (G1) in contrast to the oldest (G4) (Table 3 and Figure 8). In addition, gastrocnemius and hamstrings impact burst start-times during drop-landings with predictable response (PS) were significantly earlier than unpredictable responses (UR and UL, respectively) (Table 3 and Figure 8). A Group and Condition interaction was also found for H_tB_{Imp} (Table 3) showing that for the US drop-landings the youngest group (G1) initiate the hamstring burst earlier than older groups (G3 and

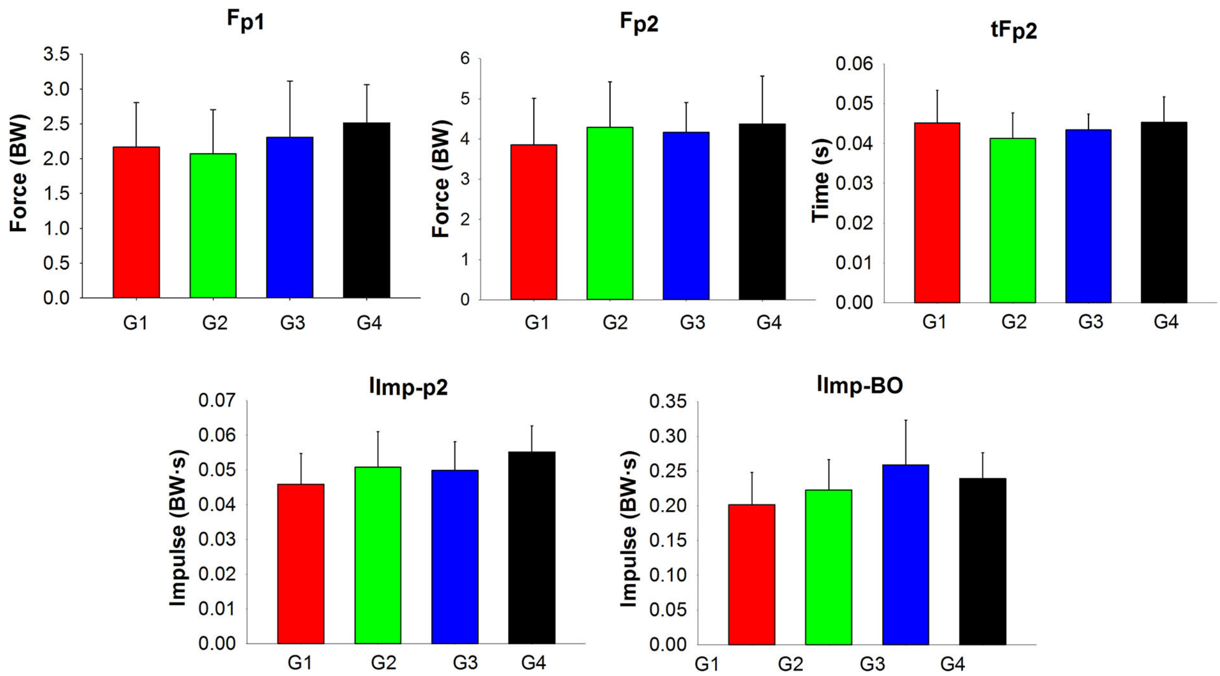

FIGURE 6
Group means and standard deviations of the kinetic variables. Despite a significant MANOVA Group effect for the kinetic parameters, no significant main group effects were found in the subsequent ANOVAs. G1, group 1 (aged 3–4.5 years); G2, group 2 (aged 4.5–6 years); G3, group 3 (aged 6–7.5 years); G4, group 4 (aged 7.5–9 years); F_{P1}, force value at peak one; F_{P2}, force value at peak two; tF_{P2}, time of peak two; I_{Imp-P2}, impulse from impact to peak two; and I_{Imp-BO}, impulse from impact to braking offset.

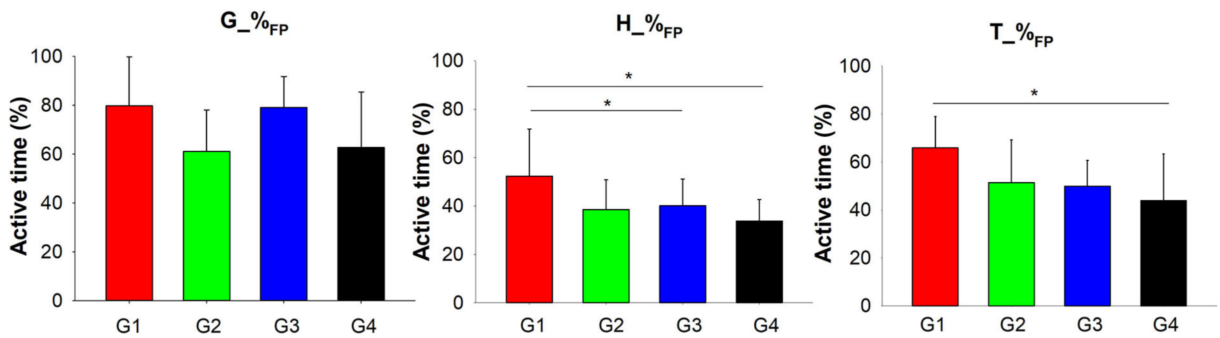

FIGURE 7
Significant Group main effects of sEMG variables. Mean and standard deviations were plotted by group. G1, group 1 (aged 3–4.5 years); G2, group 2 (aged 4.5–6 years); G3, group 3 (aged 6–7.5 years); G4, group 4 (aged 7.5–9 years); $G\_\%_{FP}$, Gastrocnemius percentage of activation during the flight phase; $H\_\%_{FP}$, Hamstrings percentage of activation during the flight phase; $T\_\%_{FP}$, Tibialis anterior percentage of activation during the flight phase. Asterisks (*) represent significant differences in the *post-hoc* analyses.

G4) (Table 3 and Figure 8) and that G3 activated earlier the hamstrings during the impact of the predictable drop-landings (PS) than the non-predictable trials (UL, UR, and US) (Table 3 and Figure 8).

Regarding the muscle patterns response to the impact, the distal sequence (Dis_EMGPattern) was mostly used by all groups but the second most frequent sequence used differed across groups (Table 5). Thereby, older groups (G3 and G4) showed higher frequencies performing mixed crossed sequences (Mix_{Cro}_EMGPattern) while G1 and G2 presented higher frequency of the mixed anterior sequence (Mix_{Ant}_EMGPattern) and the mixed posterior sequence (Mix_{Pos}_EMGPattern), respectively.

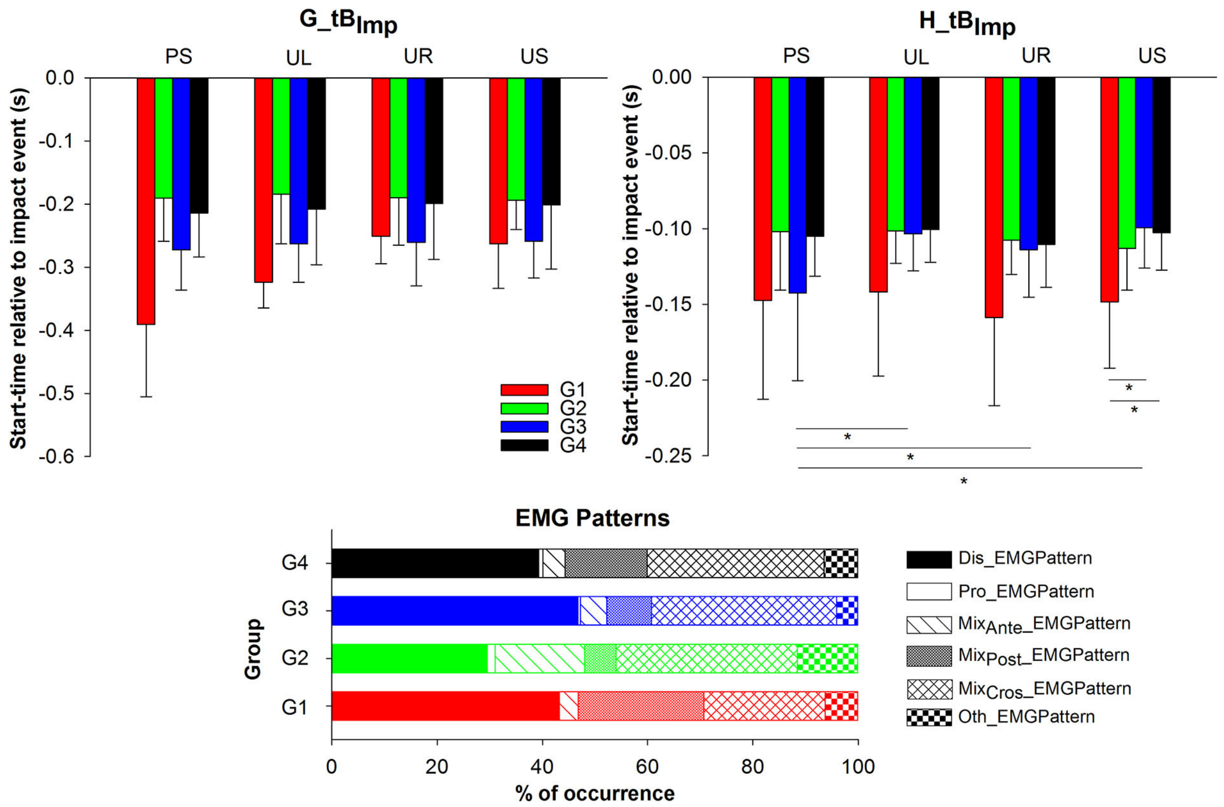

FIGURE 8
Significant Group x Condition interaction effects of the sEMG variables and occurrence of the muscle patterns in response to the impact event. Mean and standard deviations were plotted by condition and group and percentage of occurrences of the muscle patterns were plotted by group. G1, group 1 (aged 3–4.5 years); G2, group 2 (aged 4.5–6 years); G3, group 3 (aged 6–7.5 years); G4, group 4 (aged 7.5–9 years); G_tB_{Imp}, start-time of the gastrocnemius impact burst; H_tB_{Imp}, start-time of the hamstrings impact burst; PS, predictable stay condition; UL, unpredictable left condition; UR, unpredictable right condition; US, unpredictable stay condition; Dis_EMGPattern, gastrocnemius and tibialis anterior were the two first muscles activated; Pro_kinPattern, hamstrings and quadriceps were the two first muscles activated; Mix_{Ante}_EMGPattern, quadriceps and tibialis anterior were the two first muscles activated; Mix_{Post}_EMGPattern, gastrocnemius and hamstrings were the two first muscles activated; Mix_{Cros}_EMGPattern, hamstrings and tibialis anterior or gastrocnemius and quadriceps are the two first muscles activated; Oth_EMGPattern, other possible combinations when erector spinae was activated. Asterisks (*) represent significant differences in the *post-hoc* analyses.

Discussion

This multi-variant study explored how young children modified their motor strategies to drop and land across age (from 3 to 9 years) and the possible effect of landing followed by an unexpected or an expected action. Our results indicated that younger children (G1: 3–4.5 and G2: 4.5–6 years) seemed to modulate differently their drop-landing strategies but with similar effectiveness than the older groups (G3: 6–7.5 and G4: 7.5–9 years). In addition, children did not generally modify their drop-landing strategies to adapt them to unexpected or expected follow-up actions. These results only partially supported our hypothesis that less flexion would have been performed by the youngest children during the landing. Nonetheless, our study provided new evidence to the scarce literature on how landing develops during kindergarten and primary school ages using an ecological task design.

During the FP and preparing for the impact, the youngest children (G1) showed longer muscle activity of the tibialis anterior (ankle dorsi-flexor) and hamstrings (knee flexor, hip extensor) than older children (both muscles for G3, only hamstrings for G4) and earlier start of the hamstrings' impact burst than the oldest group (G4). It is proposed that muscle activation before touchdown plays a major role on the individual landing strategy. An anticipatory strategy usually presented by less experienced performers is to increase joint stiffness by increasing the antagonist muscle activity before impact (Liebermann, 2008; Wild et al., 2009; Christoforidou et al., 2017). Previous studies showed hamstrings activity in pre-pubescents [8–10 years in Russell et al. (2007); 7–8 years in Wild et al. (2009)] and an increase of the tibialis anterior activity in untrained girls (9–12 years) (Christoforidou et al., 2017) to prepare the landing. Our results seemed to indicate that the youngest children pre-activated the antagonist muscles for a longer time likely to increase joint stiffness, especially the knee, and increase passive absorption of kinetic energy.

In addition, these longer and earlier antagonist muscle activities previous to impact observed in the youngest children could also indicate differences in the learning of the control mode of the landing task. Upon landing, the onset and duration of the voluntary muscle activity seems to be mainly planned using a feedforward mode of control, which estimates the instant of impact based on the height of fall and/or the time of flight (Santello, 2005; Liebermann, 2008). Learning of this feedforward mode of control should be influenced by age and experience (Schmitz et al., 2002; Croce et al., 2004; Quatman et al., 2006; Lazaridis et al., 2010; Christoforidou et al., 2017). In fact, untrained pre-pubescent girls (9-12 years) showed shorter muscle pre-activation compared to gymnasts when exposed to increasing drop heights, which was considered as indicative of a worst estimation of the instant of impact and its consequences. Also, Rosales et al. (2018) reported that typically developing children between 3 and 4.5 years presented longer muscle bursts in comparison to children with autism spectrum disorder of the same age indicating a poor feedforward control of this last group. In our study, the height of the monkey bar was established for each child based on individual's anthropometrics and vertical jump ability (Rosales et al., 2018) and was constant across trials. Given that the height of fall was related to the height of jumps capability, it is possible that children from 4.5 years had a similar refinement of the feedforward control mode but not the youngest children (3.5–4.5 years) who had an underlearned control mode, characterized by earlier and longer antagonistic activation of hamstrings in comparison to the older groups. However, to properly study the consequences of the time to impact estimation and the feedforward control learning across ages, future studies changing the height of the bar relative to the anthropometrics characteristics and the vertical jump ability of the child are needed.

Regarding muscle coordination, time patterns of the muscle activation analyzed in this study yielded that the distal sequence was the most used for all age groups, while the proximal sequence did almost not occur. Interestingly, age-groups differed in their second most frequent sequences pointing out that children across age did not always activate muscles in the same sequence to prepare the landing. Concretely, children between 3–4.5 years relied more on performing sequences where anterior muscles of the leg (tibialis anterior and quadriceps) were the first muscles activated, while posterior muscles (gastrocnemius and hamstrings) were the two first muscles activated by children between 4.5–6 years. On the other hand, older groups (children >6 years) showed sequences where anterior and posterior muscle activations were mixed as their second most frequent muscle activity sequence. These results seemed to be partially in agreement with Jensen et al. (1994) hypothesis that timing relationship is more related to task demands (i.e., jump and land in their article) than performer skills obtained by age and/or experience. However, using a sequence where anterior or posterior muscles are the first muscles activated could be related to the estimated postural position at impact. This seemed to be clearer for the youngest children group who appeared to estimate impact with a posteriorized posture and thus they activated first the anterior leg muscles, or the second younger group, whom estimated an anteriorized posture and activated posterior leg muscles. Therefore, timing of the muscle activation would be related to task demands but also to estimation of the impact posture.

In general, no differences were found in the FP as a consequence of the knowledge or not of the task to do after landing, except for children between 6 and 7.5 years that showed earlier activation of the hamstring for the predictable response after landing trials in comparison to the non-predictable response trials. We did not expect differences between conditions when preparing the landing because cues to respond were activated after touching the force plates. In addition, previous studies in children (Rosales et al., 2018) and adults (Yom et al., 2019) using similar experimental conditions indicated that participants did not modify their flight phase regardless of the task to perform after landing. Surprisingly, G3 pre-activated earlier the hamstrings when they were aware that they had to remain stable and stationary after landing. It could be that to ensure the achievement of the task they further anticipated the time onset of the agonistic muscle activity and in consequence the stiffness of the knee.

After the impact, no differences in the muscle co-activity were observed across age groups but results seemed to indicate that younger children moved differently. The younger groups performed the absorption of the impact with less angular displacement and slower angular velocities in comparison to G3. In concrete, children between 3 and 4.5 years flexed less the knees and exhibited slower ankle dorsi-flexion during the braking phase, while smaller ankle dorsi-flexion and ankle range of motion was observed for the children between 4.5 and 6 years. It is suggested that a more efficient and mature landing performer will use multi-joint flexion of the leg and trunk to increase the duration of the post-landing period (corresponding to our braking phase) and then actively dissipate kinetic energy within a longer time period (McKay et al., 2005; Liebermann, 2008; Estevan et al., 2020). Our results are consistent with studies that proposed that less skilled children landing presented poor control of the ankle dorsiflexion (Hinrichs et al., 1985; Mckinley and Pedotti, 1992). In addition, results of our study appeared to indicate that children from 4.5 years of age already used a knee angular motion to modulate the impact effects as oldest children did. Given that all children groups presented similar co-contraction activity durations, it could be suggested that the observed differences in the knee and ankle joint motion were not so related to the control of the muscle activation but more related to the capacity to generate and control eccentric and explosive forces required to brake the landing (Jensen et al., 1994; Hass et al., 2003; Waugh et al., 2013). On the other hand, it is fair to notice that younger groups presented differences with the children of 6–7.5 years but not the oldest ones (7.5–9 years). When examining the group characteristics, the oldest group did not present the same linear change in the maximum vertical jump skill than the observed in the other age groups, while they maintained a similar linear growth as the rest of the groups. This disparity between the physical and the motor skill development could indicate that participants included in the oldest group were not as motor advanced as it would be for their age.

Furthermore, the analyzed time patterns of the joint motion after landing showed that children coordinated movements mostly using a distal sequence, while a proximal sequence was almost not used by children. Children between 6 and 7.5 years presented the lowest frequency using the distal sequence and highest use of timing patterns where the maximum knee flexion was the last to occur. Also, the older group used more frequently the distal sequence and used less the mix sequence. Regardless of these differences, our results agreed with Jensen et al. (1994) that mainly observed similar timing relationship of joint motion across ages. As the authors proposed previously it is plausible that these time patterns were related to task demands (i.e., jump and land in their article) but not necessarily to age and/or experience.

Despite the differences found during the flight and braking phases, similar kinetic values were obtained by all the age-groups demonstrating equivalent efficiency absorbing the impact. It is recommended that when the objective is to better understand developmental differences in landing strategies, it is critical to consider the relative height from which participants are required to land (task demands) (Weinhandl et al., 2015; Rosales et al., 2018). Therefore, the design of this study took extra care to control for the level of task demand and established the height to fall according to the anthropometric characteristics and the jumping ability of the child. In addition, all kinetic variables were normalized by body weight. Considering both factors (level of task demand adjustment and normalized values) could be the reason why our results did not show the age differences presented by other studies (Liebermann, 2008; Lazaridis et al., 2010; Iida et al., 2012). We recommend to compare studies using absolute different falling heights with caution and to design studies with the level of the task demand adjusted by anthropometrics and jumping ability whenever possible.

Predictable and unpredictable response after landing conditions did not affect the motor strategies performed by children during the BP. Similar results were reported for children (3–4.5 years) (Rosales et al., 2018) and adults (Yom et al., 2019) performing the same task. Our data could indicate that children between 3 and 9 years of age are not able to integrate landing and a subsequent task since we found no significant condition effects for any age group. However, taking into consideration that adults also presented the same behavioral results and that it was impossible to anticipate the response to the cue (it appeared when one foot touched the force plate), it seems reasonable to think that children did not respond to the unanticipated cues with a different or modified motor strategy.

Taking all together, evidences of this study could establish the bases from which to design physical activity session to enhance landing acquisition during childhood. We would suggest to primarily focus on intervention exercises that help to learn the feedforward control mode necessary to adequately estimate the instant of impact and, also, to improve the capacity of ankle, knee, and hips muscles to control and generate eccentric and explosive force to actively dissipate the kinematic energy instead of using muscle co-activity to adopt a stick strategy. In addition, description of the motor strategies could assist professionals to identify motor patterns of landing in non-typical developed children populations and lead possible interventions.

Regarding the contributions of this study to understand how drop-landing strategies developed during childhood and the use of relatively large sample, it has to be recognized that results are based on a cross sectional design and, then, no true developmental trajectories can be stablished. We did our best creating a set up for drop-landing similar to the one in the playgrounds; we assumed limited ecological validity data because they were collected in an experimental laboratory in favor of ensuring quality data. We only evaluated the sEMG on/off patterns and times of muscle activity to minimize the differential effects of electrode placement, movement artifact, and normalization technique. However, the proper use of the sEMG magnitude could have added information about the muscle activity level. Coordination in this study was assess using discrete outcome variables; a more accurate approach to analyze how children coordinate drop-landing would take in consideration all kinematic or sEMG measurements trajectories as a function of time. Since no differences in the motor strategies were found between unpredictable and predictable conditions in drop-landing tasks in children, it could be possible that differences appear in the motor response to the cue with longer time response. Studies to analyze motor response to unpredictable cues are needed. Researchers could design them with longer times that ensure capturing the initiation of the response and providing new insight in whether and how children modulate drop-landing strategies, both before and after initial contact with the floor. Finally, we assumed symmetry between the two legs and no sex-based differences and, maybe, some developmental achievements to perform landing are related to individual laterality or sex. Further researches are needed to cover all the above limitations but also comparisons of participants across lifespan are necessary to support our results, to assess targeted interventions or new playgrounds and kindergarten designs adapted to the youngest children characteristics.

Conclusions

In summary, our results in young children (3–9 years) suggest that drop-landing strategies were related to age or task demands but not to the predictability of the task following the land. During the FP, the youngest children (3–4.5 years) showed longer antagonist leg muscle activity likely to increase the joint stiffness or maybe because they had an underlearned feedforward control mode to estimate the instant of impact. After the impact, children between 3 and 6 years showed a poor ankle dorsiflexion while knee flexion values were smaller only for the youngest children. These results together with the lack of muscle co-activity differences across age groups could indicate a reduced capacity to control and generate the adequate amount of eccentric and explosive force to actively dissipate the kinematic energy. In addition, all children showed a preference to use a distal sequence coordinating muscle activation to prepare the impact and coordinating joint motion after the impact, while a proximal sequence was rarely used. These timing relationship results suggested that coordination could be related to task demands but not to age and/or experience. On the other hand, the differences in the second most frequent muscle activation used during the FP could be an indication that impact posture estimation could modulate the pre-impact muscle coordination. Taken all results together, children between 3 and 6 years used different drop-landing strategies than older children (6–9 years) but with similar effectiveness. The largest differences presented by the youngest group could indicate that a developmental critical point in landing performance exists at 4–5 years of age. We would suggest to start targeted practice and interventions around this age together with studies examining the feasibility to conduct them in playgrounds and kindergarten environments.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Institutional Review Board at California State University, Northridge (CA, USA). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

RA-B contributed with the conception of the idea, design of the study, and the implementation of the research. JJ and RA-B contributed by providing sEMG burst analysis methodology and the custom made software to implement it. AB and BF-U contributed with the data treatment, variables calculation, and statistical analyses. All authors contributed to data analysis and writing of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Maurice Mohr,
University of Innsbruck, Austria

*CORRESPONDENCE
Marit A. Zandbergen
✉ m.zandbergen@ocon.nl

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Quantifying and correcting for speed and stride frequency effects on running mechanics in fatiguing outdoor running

Marit A. Zandbergen[1,2]*, Jaap H. Buurke[1,2], Peter H. Veltink[1] and Jasper Reenalda[1,2]

[1]Department of Biomedical Signals and Systems, Faculty of Electrical Engineering, Mathematics and Computer Science, University of Twente, Enschede, Netherlands, [2]Department of Rehabilitation Technology, Roessingh Research and Development, Enschede, Netherlands

Measuring impact-related quantities in running is of interest to improve the running technique. Many quantities are typically measured in a controlled laboratory setting, even though most runners run in uncontrolled outdoor environments. While monitoring running mechanics in an uncontrolled environment, a decrease in speed or stride frequency can mask fatigue-related changes in running mechanics. Hence, this study aimed to quantify and correct the subject-specific effects of running speed and stride frequency on changes in impact-related running mechanics during a fatiguing outdoor run. Seven runners ran a competitive marathon while peak tibial acceleration and knee angles were measured with inertial measurement units. Running speed was measured through sports watches. Median values over segments of 25 strides throughout the marathon were computed and used to create subject-specific multiple linear regression models. These models predicted peak tibial acceleration, knee angles at initial contact, and maximum stance phase knee flexion based on running speed and stride frequency. Data were corrected for individual speed and stride frequency effects during the marathon. The speed and stride frequency corrected and uncorrected data were divided into ten stages to investigate the effect of marathon stage on mechanical quantities. This study showed that running speed and stride frequency explained, on average, 20%–30% of the variance in peak tibial acceleration, knee angles at initial contact, and maximum stance phase knee angles while running in an uncontrolled setting. Regression coefficients for speed and stride frequency varied strongly between subjects. Speed and stride frequency corrected peak tibial acceleration, and maximum stance phase knee flexion increased throughout the marathon. At the same time, uncorrected maximum stance phase knee angles showed no significant differences between marathon stages due to a decrease in running speed. Hence, subject-specific effects of changes in speed and stride frequency influence the interpretation of running mechanics and are relevant when monitoring, or comparing the gait pattern between runs in uncontrolled environments.

KEYWORDS
marathon, kinematics, inertial measurement unit, biomechanics, acceleration, endurance

Highlights

- Effects of changes in speed and stride frequency on mechanics are subject-specific
- Speed and stride frequency explain 20%–30% of the variance in PTA and knee angles
- Changes in speed and stride frequency masked fatigue-related changes in mechanics
- Correct mechanics for changes in speed and stride frequency in outdoor running

1. Introduction

Motion analysis in running provides objective information about running technique. This information can be used to improve running performance (1, 2), monitor effects of fatigue on the gait pattern (3, 4), and possibly reduce injury risk through real-time feedback on mechanical quantities (5–7). Feedback is often provided on peak tibial acceleration (PTA) since this quantity is easy to measure and provides information about a combined effect of impact forces and running technique on the acceleration of the tibia (8). However, PTA is not directly linked to forces in the body since PTA is unable to represent the contribution of muscle contractions (9, 10). Monitoring of knee angles is of interest due to their role in shock attenuation during running (11) and their tendency to change with running-induced fatigue (9, 10, 12).

Traditionally, running mechanics were measured in a gait laboratory. A laboratory setting allows researchers to control or minimize influences on the gait pattern from, for instance, running speed, inclination, running surface, and the weather. Simultaneously, a laboratory setting is restricted to an artificial environment that is not sport-specific. Multiple mechanical quantities concerning peak accelerations and shock attenuation showed important differences between overground and treadmill running (13–16). Hence, running mechanics should be analyzed in a representative environment since findings from laboratory-based treadmill studies cannot easily be generalized to overground running (14, 17, 18).

One essential difference between treadmill and outdoor running is the ability to adapt running speed. Most runners lower their speed after prolonged running due to fatigue (19, 20). The influence of running speed and stride frequency on mechanical variables has extensively been studied in controlled environments and typically on a treadmill. PTA increases with an increase in running speed (8) or a decrease in stride frequency (21). PTA showed a strong significant linear regression with speed in treadmill running (22, 23). Individual variances in these relationships were large, highlighting the need for subject-specific analysis (22, 24). Additionally, maximum stance phase knee flexion increased with an increase in speed or a decrease in stride frequency (25, 26). No speed effect on knee flexion angles at initial contact was found over a small range of running speeds in recreational runners (26). Hence, running speed and stride frequency influence PTA and knee joint angles in running which makes it hard to compare quantities both within and between runs when speed and stride frequencies are not consistent. Two previous studies corrected mechanical quantities during running in an uncontrolled setting for speed by computing individual ratios (i.e., dividing by speed) (19, 20). This correction assumes that the relationship between speed and quantities of interest crosses the origin (i.e., quantity of interest is zero when the speed is zero) and is linear over the full range of running speeds for all subjects. Such a relationship assumes that an increase in speed of 1 km/h during walking and running will result in the same increase in a quantity of interest. However, in the case of PTA, the regression equation between speed and PTA differs between foot strike patterns (20), between subjects (24) and the intercepts of group-based analyses do not appear to cross the origin (20). Thus, individual ratios likely oversimplify the relationship between speed and quantities of interest.

Inertial measurement units (IMUs) can measure running mechanics in a sport-specific setting and open up new possibilities for real-time feedback on running technique in a representative environment (18). Feedback on PTA values is often used to improve running technique by providing warnings for high PTA values, both in commercial devices and in research (27–31). Additionally, algorithm development allows the estimation of knee angles based on a minimal sensor set (32). Feedback on running technique is often based on an arbitrary fixed threshold independent of running speed and stride frequency which can mask fatigue-related changes in running biomechanics. Without correcting for the effects of speed and stride frequency, the origin of changes is unclear, preventing appropriate interpretation and feedback on running biomechanics. Hence, this study aims to quantify and correct for the subject-specific effect of running speed and stride frequency on changes in impact-related running mechanics during a fatiguing outdoor run.

A marathon was used as an uncontrolled setting to ensure that a wide range of external influences (e.g., fatigue, different surfaces, other runners) found in typical uncontrolled outdoor running were incorporated to improve the ecological validity of relationships. We hypothesized that:

1. Running speed and stride frequency decrease toward the end of the marathon
2. The influence of running speed and stride frequency on PTA, knee angles at initial contact, and maximum stance phase knee flexion angles differs between subjects
3. Correcting PTA and knee angles for subject-specific changes in speed and stride frequency results in significant changes during the marathon which are not found in uncorrected values

2. Methods

2.1. Participants

Nine healthy recreational runners participated in this study. Technical errors resulted in missing data for two subjects. Therefore, data from three females and four males were included (mean (standard deviation); age: 36 (11) years, height: 181 (5) cm, mass: 74 (8) kg, running experience: 7 (4) years). All subjects gave written informed consent before participating in this study. The Ethics Committee Computer and Information Science of the University of Twente approved the study protocol.

2.2. Measurement systems

Subjects were equipped with eight IMUs (sampling frequency: 240 Hz, dimensions: $36 \times 25 \times 10$ mm, weight: 16 g, MVN Link, Xsens Technologies, Enschede, The Netherlands). IMUs were placed on the sternum, back of the pelvis, and bilaterally on the midportion of the lateral upper leg, proximally on the tibia, and on the midfoot. Hair on the skin was shaved to improve IMU attachment before IMUs were fixed to the skin with double-sided tape and covered with additional tape. IMUs on the midfoot were placed under the tongue of the shoes. Wires between IMUs were loosely taped to the skin to prevent entanglement, see **Figure 1**. IMUs were connected with a bodypack and battery pack. The bodypack delivered power from the battery pack to the IMUs and synchronized and stored data from the IMUs on internal memory. The bodypack and battery pack weighed 220 grams (33) and were placed in a neoprene storage belt around the waist of the runners. Subjects used their personal sports watches with a global navigation satellite system (GNSS), measuring coordinates with different sampling frequencies of on average 0.7 (0.4 Hz).

FIGURE 1
One of the runners a few meters before the finish line. The bodypack and battery pack are placed in the pink belt. White tape is visible, which covers the sensors and fixates sensor wires.

2.3. Measurement protocol

Measurements were performed during the Enschede marathon (42.195 km) in the Netherlands on a typical Dutch spring day with temperatures around 10°C. The course was relatively flat, with about 42 meters of elevation and was performed in relatively open space (i.e., no woods) on the road. The track consisted of two laps of which about 60% of the course was identical between laps. Before the marathon, multiple anthropometric values were measured (body height, hip height, hip width, knee height, ankle height, and shoe length). Sensor-to-segment calibration was performed according to the manufacturer's recommendations (34). Subjects were instructed to run their marathon as planned and not to worry about the equipment.

2.4. Data analysis

The data presented in this study are openly available on figshare (https://doi.org/10.6084/m9.figshare.22331686.v1).

2.4.1. Data extraction and computing speed

Sensor data was extracted from the internal memory of the bodypack. Sensor acceleration, angular velocity, and magnetometer data were used to estimate sensor orientations in the software package Xsens MVN Analyze (version 2019.2.1). A scaled biomechanical model was created based on anthropometric measurements, raw sensor data (accelerations and angular velocities), and estimated sensor orientations. Knee flexion angles and pelvis IMU velocity were obtained from this scaled biomechanical model (34). Latitude and longitude coordinates were extracted from the GNSS data. Missing latitude-longitude coordinates were linearly interpolated before speed was computed as the distance between two latitude-longitude coordinates based on the Haversine formula (35). Speeds above 20 km/h were deemed extremely unlikely and replaced with spline interpolation. Speed was then resampled to 240 Hz to match the sampling frequency of the IMUs.

2.4.2. Temporal synchronization

GNSS and IMU data were temporally aligned based on GNSS speed and speed of the pelvis IMU. Pelvis IMU speed was computed as the resultant pelvis IMU velocity obtained from the scaled biomechanical model. GNSS and IMU data were then synchronized by cross-correlating GNSS speed with pelvis IMU speed. Temporal alignment between both systems was visually checked at the start and end of the marathon to ensure that possible differences in internal clocks would not influence temporal alignment. Visual misalignment was present in data of one subject, for which IMU data was resampled based on cross-correlation of the first and last 20% of the data points separately.

2.4.3. Removing walking parts and segmentation

Some participants walked for short periods during the marathon to drink something or due to fatigue. PTA is higher for running than for walking (36). Walking parts were detected and removed based on a minimum of two adjacent outliers in PTA of the right leg. In this case, an outlier was defined as a PTA value of more than four scaled median absolute deviations below the median over the complete marathon. The median absolute deviation is computed as the median of absolute deviations from the median value (37). The median absolute deviation is then scaled by multiplying by 1.48 to approximate the standard deviation as typically reported in literature (38). Additionally, ten strides before and after a walking part were removed to omit the effect of slowing down and increasing speed. After removing the walking parts, data were segmented into time-normalized gait cycles starting with initial contact based on right foot accelerations (39).

2.4.4. Extracting quantities of interest and removing outliers

Quantities of interest were computed for the right legs from all subjects. PTA was defined as the positive acceleration peak in the axial direction of the tibia in a sensor-fixed coordinate system during the first 33% of the gait cycle. Accelerations in the axial direction compared to the resultant acceleration were chosen to better represent the main direction of impact forces in the body. Knee flexion angles were defined as 0° when the leg was fully extended, and flexion resulted in positive values. The knee angle at initial contact was extracted from the first sample of the time-normalized gait cycle. Maximum stance phase knee flexion was defined as the maximum knee angle during the first 33% of the gait cycle. Stride frequency (strides/minute) was based on the time between two right initial contacts. Speed was averaged over the complete gait cycle. The average foot strike angle (i.e., angle between the foot and horizontal in the sagittal plane at initial contact) over the complete marathon was computed to determine the foot strike pattern of subjects (40). Outliers in quantities of interest were defined as values deviating more than four scaled median absolute deviations from the moving median over a window of 500 strides. A relatively large deviation from the median value was chosen to classify outliers to prevent removal of a considerable amount of data and over-smoothing the data. All strides with an outlier in any of the quantities of interest were removed from further analyses.

Median values over segments of 25 strides were computed, and outliers were removed (>4 scaled median absolute deviation from moving median over a window of 500 segments) to improve data stability and reduce the amount of data (41). The marathon was divided into ten stages to investigate the effect of marathon stage; each stage was roughly equal to 4 km of running data. Mean values for each stage of the marathon were computed from the earlier defined median values, see **Figure 2**.

2.5. Statistical analysis

Group-based one-way repeated measures ANOVAs were performed to test whether running speed, stride frequency, PTA, knee angles at initial contact, and maximum stance phase knee flexion changed over the different stages of the marathon. The ANOVAs had ten levels (stages of the marathon), and the mean values for each subject for all ten stages were used as input. When a significant effect of marathon stage on one of the quantities of interest was found, *post hoc* tests were used to test which marathon stages differed from each other.

Subject-specific multiple linear regression models were created to test if running speed and stride frequency could predict PTA, knee angles at initial contact, and maximum stance phase knee flexion angles. Median values for all 25 stride segments were used as input for the regression models, and no distinction for marathon stage was made. Intercepts and coefficients from the subject-specific regression equations were used to correct PTA and knee angles for the subject-specific effect of changes in speed and stride frequency. PTA and knee angles were corrected for individual changes in speed by subtracting the individual coefficients for speed (i.e., output of the multiple linear regression model) multiplied with the deviation from the individual mean speed for all segments of 25 strides during the marathon. Corrections for individual changes in stride frequency were performed similarly. Effectively, this method recomputes the quantities of interest as if the speed and stride frequency were equal to the average speed and stride frequency during the whole marathon.

Group-based one-way repeated measures ANOVAs (10-levels) were repeated to test whether speed and stride frequency corrected PTA, knee angles at initial contact, and maximum stance phase knee flexion changed over the different stages of the marathon.

An alpha level of 0.05 was used to determine statistical significance. When applicable, Holm-Bonferroni corrections were applied for all possible 45 *post hoc* pairwise comparisons. Correlations were interpreted as very strong $r = (0.90, 1.00)$, strong for $r = (0.70, 0.89)$, moderate for $r = (0.40, 0.69)$, weak for $r = (0.20, 0.39)$ and very weak for $r = (0.00, 0.19)$ (42). Statistical analyses were performed in JASP (version 0.16.3).

3. Results

Subjects finished the marathon in 3 h and 55 min (30 min), with an average speed of 11.0 (1.5) km/h and an average stride frequency of 85.6 (2.9) strides/minute. Walking parts resulted in the removal of 2.7 (2.1)% of all data points. An average of 19,383 (2,073) gait cycles were measured per runner, of which 8.8 (2.4)% was removed due to outliers. Runners 1 and 5 were classified as non-rearfoot strikers based on a foot contact angle smaller than 8° (40).

3.1. Speed and stride frequency

There was a statistically significant effect of marathon stage on speed on a group level, $F(9,54) = 5.766$, $p < 0.001$, see **Figure 3**. Running speed decreased from 11.5 (1.8) km/h to 10.3 (1.4) km/h between the first and last stages of the marathon. Post-hoc analyses showed that speed during the last two stages was lower than in the first four stages of the marathon. No significant effect of marathon

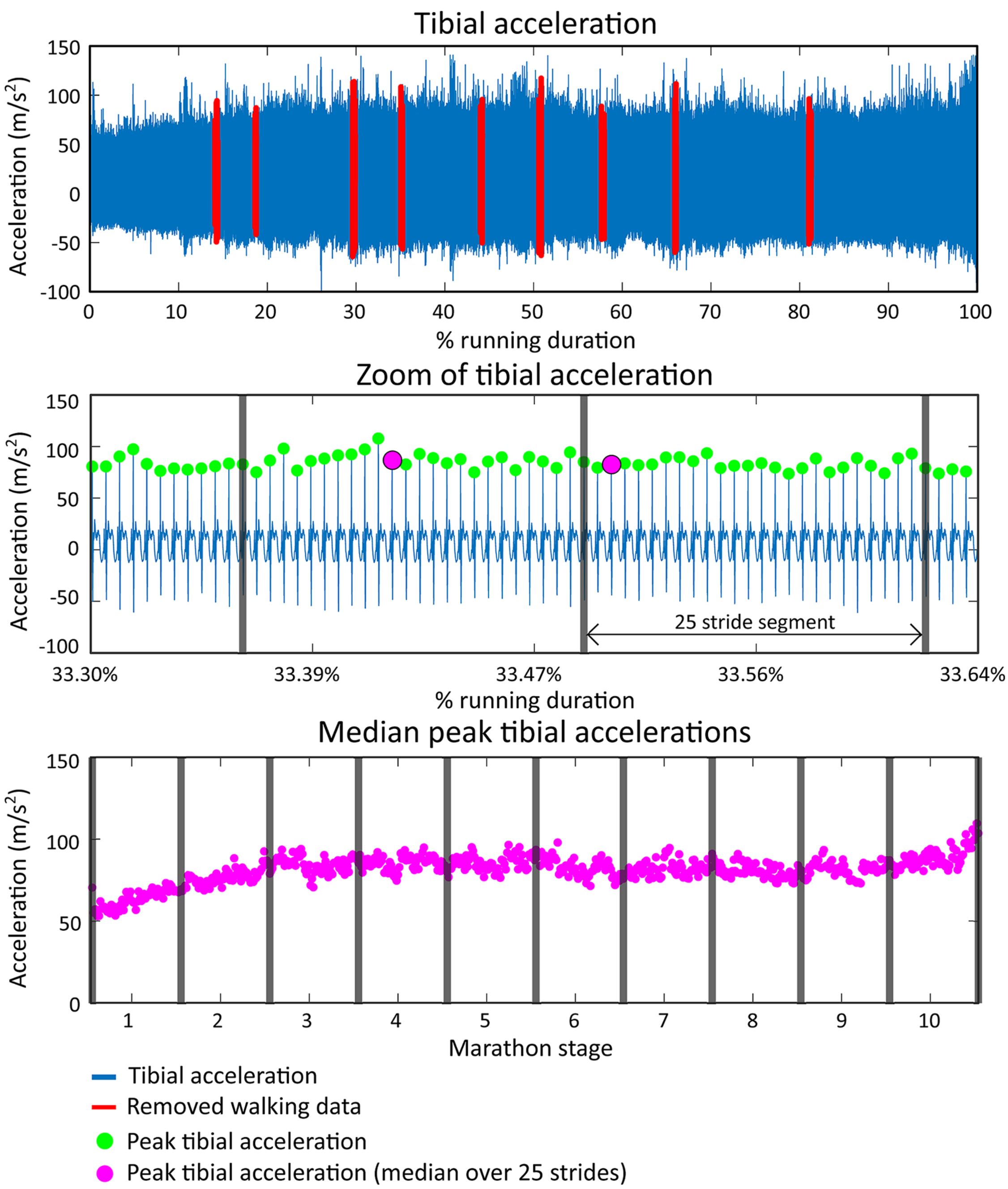

FIGURE 2
Data extraction shown for peak tibial acceleration (PTA). The top figure shows the tibial acceleration of a representative runner (runner 7) during the full marathon. Walking parts are labeled red and removed from further analysis. The middle figure shows a snapshot of the tibial acceleration signal in which PTAs are shown with green dots. Vertical grey lines show segments of 25 strides from which the median PTA is computed and shown as a pink dot. The bottom figure shows all median PTA values during the marathon. The full marathon duration is divided into ten stages for group-based statistical analyses.

stage on stride frequency was found on a group-level, $F(9,54) = 0.725$, $p = 0.684$. Speed and stride frequency were weakly correlated on a group level, $r = 0.21$ (0.18).

3.2. Peak tibial acceleration

On a group level, PTA had a moderate positive correlation with speed [$r = 0.40$ (0.24)] and no correlation was present with stride frequency due to large variability between subjects [$r = -0.09$ (0.20)], see Table 1. Subject-specific multiple linear regression equations to predict PTA based on speed and stride frequency were significant for all subjects and explained 26 (18)% of the variance in PTA, see Figure 4. Speed was a significant predictor of PTA for all runners while stride frequency was a significant predictor for all but one runner. On a group level, there was a statistically significant effect of marathon stage on PTA both for uncorrected [$F(9,54) = 2.786$, $p = 0.009$] and speed and stride frequency corrected

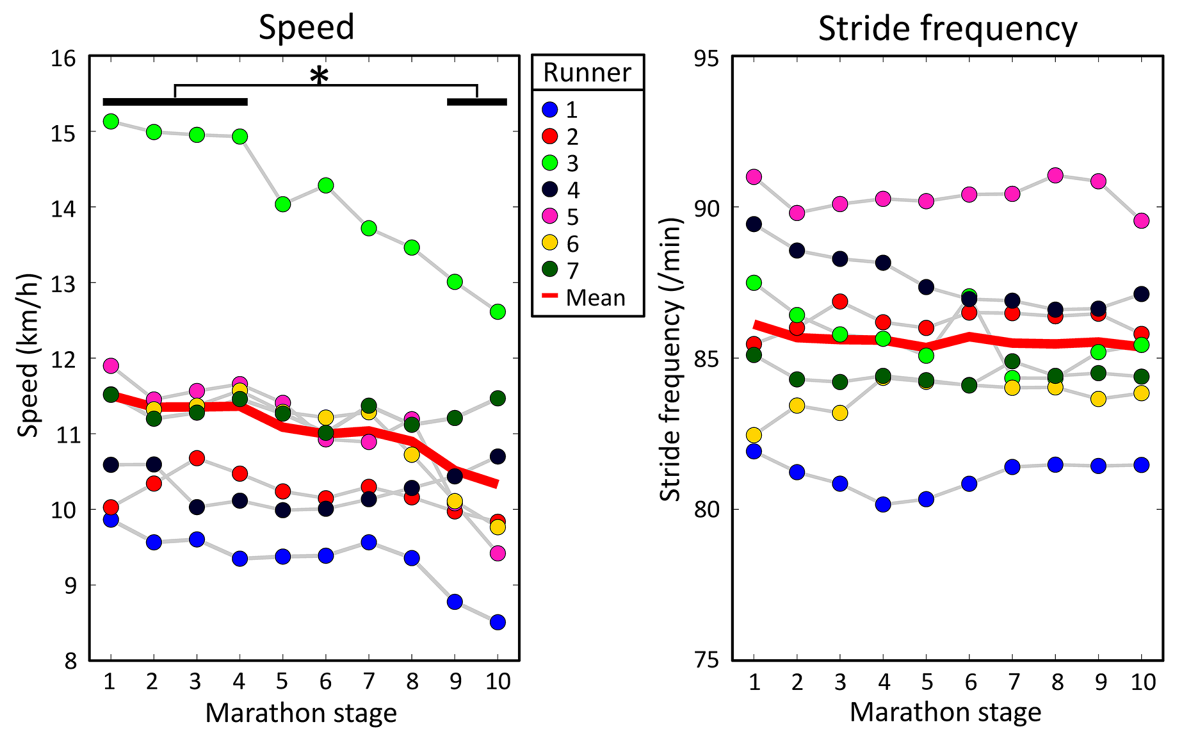

FIGURE 3
Mean speed and stride frequency for every runner during all marathon stages. The solid red lines show the group means. A significant effect of marathon stage on speed was found. Significant results from *post hoc* analyses are shown by an asterisk at the top of the figure.

TABLE 1 Left side of table: individual correlations of peak tibial acceleration (PTA) with speed and stride frequency (SF). Right side of table: Individual regression equations to predict PTA based on speed and stride frequency together with the adjusted R-squared value (i.e., explained variance of regression equation). r, Pearson's correlation coefficient; SD, standard deviation; ns, non-significant finding; NRF, non-rearfoot striking subject.

PTA	Correlation		Regression			
	Speed (r)	SF (r)	Intercept	Coefficient speed $\left(\frac{m/s^2}{km/h}\right)$	Coefficient SF $\left(\frac{m/s^2}{strides/min}\right)$	Adjusted R^2
Runner 1^{NRF}	0.48	−0.22	148.18	4.14	−1.37	0.31
Runner 2	0.33	0.11	65.78	3.75	-0.31^{ns}	0.11
Runner 3	0.55	0.11	106.14	4.83	−0.77	0.32
Runner 4	0.17	−0.21	115.32	1.45	−0.93	0.08
Runner 5^{NRF}	0.79	0.12	23.27^{ns}	7.76	−0.43	0.62
Runner 6	0.44	−0.17	114.41	2.00	−0.89	0.21
Runner 7	0.06^{ns}	−0.39	479.17	1.53	−4.92	0.16
Mean (SD)	0.40 (0.24)	−0.09 (0.20)	150.32 (150.50)	3.64 (2.26)	−1.37 (1.60)	0.26 (0.18)

values [F(9,54) = 2.316, $p = 0.028$]. However, *post hoc* analyses only showed significant differences in PTA between marathon stages after correcting for speed and stride frequency, see Figure 5. *Post hoc* analysis showed that PTA corrected for speed and stride frequency was higher in the third [77.5 (17.3)] compared to the first stage of the marathon [71.0 (17.5)].

3.3. Knee angle at initial contact

On a group level, knee angles at initial contact showed a weak negative correlation with speed [$r = -0.24$ (0.30)] and no correlation was present with stride frequency due to large variability between runners [$r = -0.03$ (0.28)], see Table 2. Subject-specific multiple linear regression equations to predict knee angles at initial contact based on speed and stride frequency were significant for all subjects and explained 20 (10)% of the variance in knee angles at initial contact, see Figure 6. Speed was a significant predictor of knee angles at initial contact for all runners while stride frequency was a significant predictor for all but two runners. On a group level, there was a statistically significant effect of marathon stage on both corrected [F(9,54) = 5.136, $p < 0.001$] and uncorrected knee angles at initial contact [F(9,54) = 7.227, $p < 0.001$]. *Post hoc* analyses showed that knee angles at initial contact during later stages of the marathon were significantly higher than during the first stages of the marathon, see Figure 6.

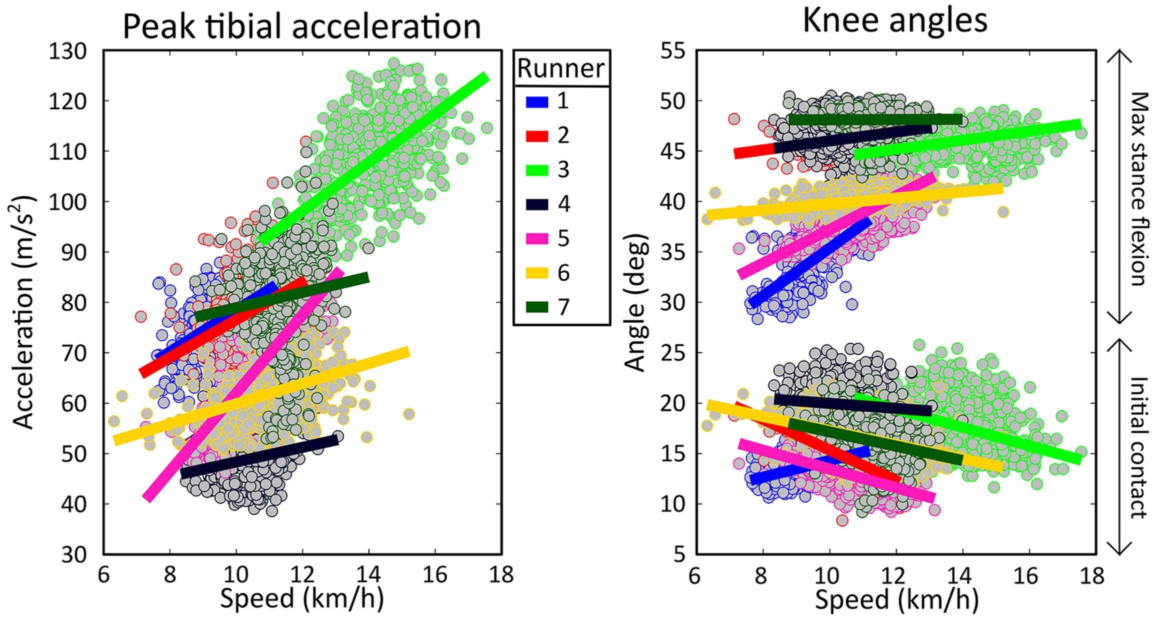

FIGURE 4
Scatterplot of individual peak tibial acceleration and knee angle values as a function of speed. Each dot represents the median value over a segment of 25 strides during the marathon. Subject-specific linear regressions are shown as solid lines.

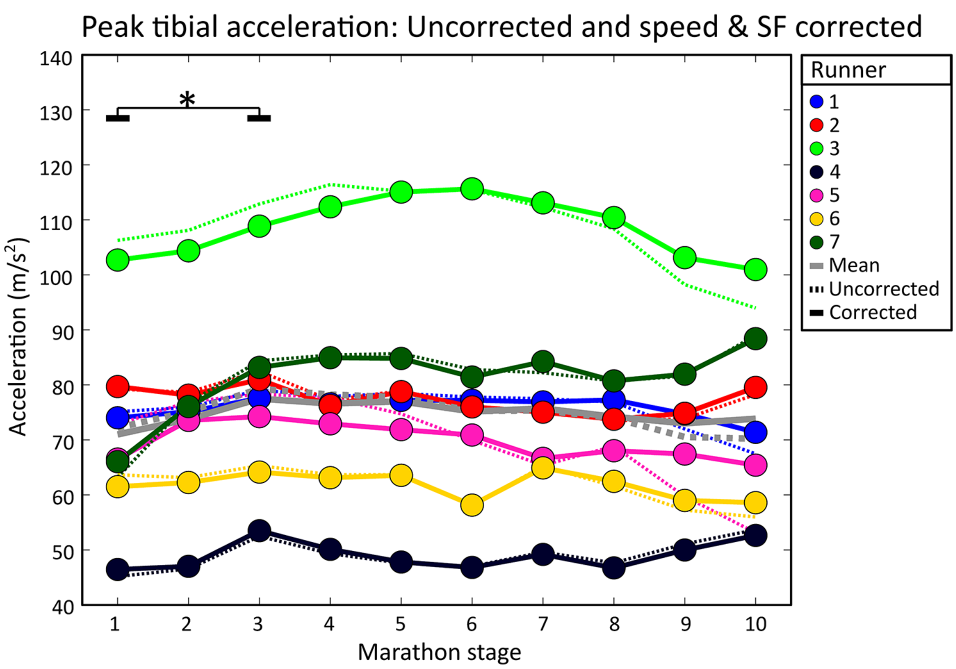

FIGURE 5
Individual mean peak tibial accelerations during all marathon stages. Dotted lines show uncorrected PTA values (i.e., as measured during the marathon). Solid lines represent speed and stride frequency corrected PTA values. Grey lines show the group means. Significant effects of running duration are shown with an asterisk and black lines. Solid black lines represent significant differences in corrected PTA values.

3.4. Maximum stance phase knee angles

On a group level, maximum stance phase knee angles had a weak positive correlation with speed [$r = 0.32$ (0.27)] and a weak negative correlation with stride frequency [$r = -0.21$ (0.28)], see **Table 3**. Subject-specific multiple linear regression equations to predict maximum stance phase knee angles based on speed and stride frequency were significant for all subjects

TABLE 2 Left side of table: individual correlations of knee angles at initial contact (IC) with speed and stride frequency (SF). Right side of table: Individual regression equations to predict knee angles at IC based on speed and stride frequency together with the adjusted R-squared value (i.e., explained variance of regression equation). r, Pearson's correlation coefficient; SD, standard deviation; ns, non-significant finding; NRF, non-rearfoot striking subject.

Knee IC	Correlation		Regression			
	Speed (r)	SF (r)	Intercept	Coefficient speed $\left(\frac{deg}{km/h}\right)$	Coefficient SF $\left(\frac{deg}{strides/min}\right)$	Adjusted R^2
Runner 1[NRF]	0.37	0.02 [ns]	10.08	0.83	−0.05 [ns]	0.13
Runner 2	−0.44	−0.24	44.34	−1.52	−0.16 [ns]	0.19
Runner 3	−0.29	0.06 [ns]	2.04 [ns]	−0.91	0.33	0.12
Runner 4	−0.15	−0.42	78.54	−0.25	−0.64	0.18
Runner 5[NRF]	−0.51	0.19	−17.90	−0.93	0.45	0.36
Runner 6	−0.43	0.40	−45.22	−0.70	0.83	0.32
Runner 7	−0.25	−0.21	67.32	−0.71	−0.51	0.09
Mean (SD)	−0.24 (0.30)	−0.03 (0.28)	19.89 (45.40)	−0.60 (0.73)	0.04 (0.53)	0.20 (0.10)

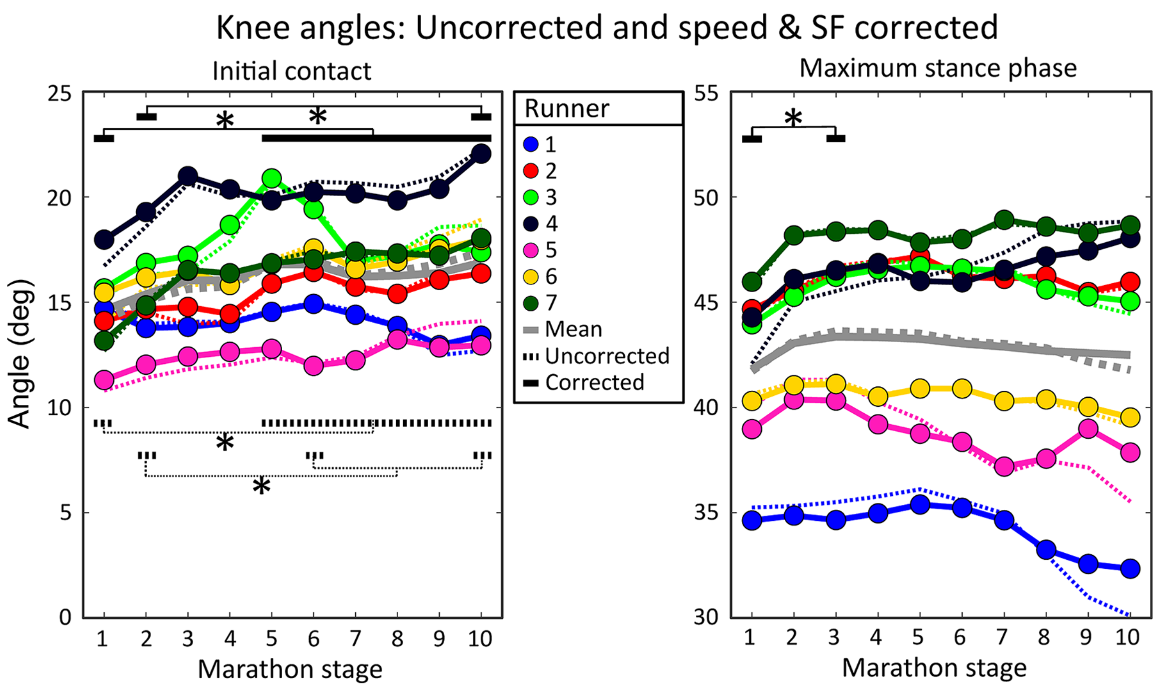

FIGURE 6
Individual mean knee angles during all marathon stages. The left figure shows knee angles at initial contact, while the right figure shows maximum stance phase knee flexion angles. Dotted lines show uncorrected knee angles (i.e., as measured during the marathon). Solid lines represent speed and stride frequency corrected knee angles. Dotted black lines represent significant differences in uncorrected knee angles while solid black lines represent significant differences in knee angles corrected for the effect of changes in speed and stride frequency. Grey lines show the group means. Significant effects of marathon stage are shown with an asterisk and black lines.

and explained 30 (20)% of the variance in maximum stance phase knee angles, see Figure 6. Speed was a significant predictor for maximum stance phase knee angles for all runners while stride frequency was a significant predictor for all but one runner. On a group level, marathon stage had no statistically significant effect on maximum stance phase knee flexion [$F(9,54) = 1.770$, $p = 0.096$]. After correcting knee angles for subject-specific effects of speed and stride frequency, a significant effect of marathon stage on maximum stance phase knee flexion was found [$F(9,54) = 2.294$, $p = 0.029$]. *Post hoc* analyses showed that the maximum stance knee flexion corrected for speed and stride frequency was significantly higher in the third [43.4 (4.9)] compared to the first stage of the marathon [41.8 (4.0)], see Figure 6.

4. Discussion

This research aimed to quantify and correct for the subject-specific effect of changes in running speed and stride frequency on impact-related running mechanics during a fatiguing outdoor run. In line with our first hypothesis, speed decreased throughout the

TABLE 3 Left side of table: individual correlations of maximum stance phase knee angles with speed and stride frequency (SF). Right side of table: Individual regression equations to predict maximum stance phase knee angles based on speed and stride frequency together with the adjusted Rsquared value (i.e., explained variance of regression equation). r, Pearson's correlation coefficient; SD, standard deviation; ns, non-significant finding; NRF, non-rearfoot striking subject.

Knee stance	Correlation		Regression			
	Speed (r)	SF (r)	Intercept	Coefficient speed $\left(\frac{deg}{km/h}\right)$	Coefficient SF $\left(\frac{deg}{strides/min}\right)$	Adjusted R^2
Runner 1[NRF]	0.59	−0.27	76.58	2.37	−0.80	0.48
Runner 2	0.31	0.25	25.13	0.45	0.19	0.11
Runner 3	0.22	−0.22	62.92	0.45	−0.27	0.17
Runner 4	0.03[ns]	−0.69	152.86	0.44	−1.27	0.49
Runner 5[NRF]	0.69	−0.08	63.90	1.67	−0.48	0.54
Runner 6	0.42	−0.17	48.46	0.30	−0.14	0.20
Runner 7	−0.04[ns]	−0.30	89.40	0.01[ns]	−0.49	0.09
Mean (SD)	0.32 (0.27)	−0.21 (0.28)	74.18 (40.27)	0.81 (0.86)	−0.47 (0.47)	0.30 (0.20)

marathon, however, no effect of marathon stage on stride frequency was found. Running speed and stride frequency explained, on average 20%–30% of the variance in PTA, knee angles at initial contact, and maximum stance phase knee flexion while running in an uncontrolled setting. Regression coefficients for speed and stride frequency varied strongly between subjects, supporting our second hypothesis. Our third hypothesis was not supported for PTA and knee angles at initial contact, but was supported by a significant change in maximum stance phase knee flexion corrected for changes in speed and stride frequency, while uncorrected values showed no significant change during the marathon.

4.1. Speed and stride frequency

Running speed significantly decreased during the marathon. A decrease in speed during a marathon is typically found (19, 20, 43, 44) and is likely caused by fatigue, although race strategy can also play a role. Stride frequency did not show a significant effect of marathon stage and was weakly correlated with speed, indicating that, similar to previous studies, the speed reduction is generally caused by a decrease in stride length instead of stride frequency (19, 45). The significance of predictors, regression equations, and explained variances differed between subjects. Differences might be caused by differences in body weight, ankle angle at initial contact (46), foot strike pattern (20), individual differences in adaptations to speed by increasing step length vs. stride frequency, differences in the tolerance to effects of fatigue and differences in the capacity to sustain a stable gait pattern over a range of speeds. Even though stride frequency did not change on a group level, adding stride frequency to the regression models resulted in significantly better predictions for almost all runners, emphasizing the benefits of subject-specific analysis vs. group-based analysis.

4.2. Peak tibial acceleration

Average group-based PTA values (81.2 ± 8.4 m/s^2) showed a significant main effect of marathon stage, although *post hoc* analyses showed no differences between marathon stages for uncorrected values. PTA values were within the range found in literature (49.1–116.7 m/s^2) (8, 20, 47). The correlations between PTA and speed [$r = 0.40$ (0.24)] during a marathon were similar to the correlations between resultant PTA and speed in controlled settings ($r = 0.42$) (24). Subject-specific multiple linear regressions showed that, on average, PTA increased with 3.6 m/s^2 for every 1 km/h increase in speed, although subject-specific coefficients ranged from 1.5 to 7.8 m/s^2. The speed coefficient of PTA was between 4.1 and 6.7 m/s^2 in controlled settings (23, 48). The speed coefficient to predict PTA in our study was generally lower than in laboratory-based studies, possibly due to the inclusion of stride frequency or external influences like fatigue. Foot strike pattern has been shown to influence the speed coefficient of PTA during a marathon. Rearfoot striking runners showed higher speed coefficients (12.8 m/s^2) than midfoot striking runners (7.0 m/s^2), while no significant speed coefficient was found for forefoot striking runners (20). In our study, the two non-rearfoot striking runners (subjects 1 and 5) had amongst the highest speed coefficients, which is possibly an effect of group- vs. subject-based analysis. The regression equation explained, on average, 26 (18)% of the variance in PTA. Although relatively low, it is higher than the 19% of explained variance in resultant PTA found in laboratory-based studies (24). To accurately predict PTA in outdoor environments, more variables are needed in the multiple linear regression equation (e.g., knee angle at initial contact), but for the scope of this paper, we were solely interested in the explained variance by speed and stride frequency. After correcting PTA for the subject-specific effects of speed and stride frequency, *post hoc* tests showed a significant increase in PTA between the first and third stages of the marathon. While this increase in PTA occurred very early on in the marathon, it is not uncommon for peak accelerations to increase during early stages of a fatiguing protocol (49–51). An increase in PTA corrected for changes in speed and stride frequency could indicate a decrease in the runner's capacity to attenuate shocks. Alternatively, the effective mass (i.e., the portion of body mass that is decelerated upon ground contact) can decrease with an increased rearfoot or knee flexion angle and increase with a more vertical lower leg at initial contact (46, 52). A smaller effective mass is easier to accelerate, which results in higher leg accelerations when similar ground reaction forces are applied. High PTA values have long been thought to be an indicator of injury risk based on retrospective studies showing that PTA was higher in previously injured compared to uninjured runners (53, 54). The repetitiveness of high forces on tissues inside the body are thought to be related to the development of running injuries (55). However, PTA is uncapable to represent tibial bone loading since it does not represent forces caused by muscle contractions in the body (9, 10). Hence, high PTA values are no indicator of injury risk on their own but do provide information about a combined effect of impact forces and running technique on the body during running.

4.3. Knee angles

Average knee angles at initial contact (16.1 (2.5)°) and maximum stance phase knee angles (42.9 (5.1)°) were within the range reported in literature, respectively 9.5°–19.5° and 31.0°–56.2° (4, 26, 52, 56, 57). Knee angles at initial contact showed a negative weak and very weak correlation with speed and stride frequency, indicating more knee extension with higher speeds and stride frequencies. Previously, the knee flexion angle at initial contact remained similar (26) or increased with speed (58), although the range of speeds included was drastically higher than those found during the marathon. A decrease in knee angle at initial contact with an increase in speed might be a strategy to increase stride length by increasing leg extension. Knee angles at initial contact corrected for subject-specific effects of changes in speed and stride frequency showed a similar increasing pattern during the marathon compared to uncorrected values. Knee angles at initial contact have been found to increase with fatigue in controlled settings (12, 52, 57), possibly to decrease vertical ground reaction forces (46) at a higher metabolic cost (59). Hence, the increase in knee angles at initial contact during a marathon is not solely an effect of changes in speed and stride frequency but is likely a result of fatigue.

Maximum stance phase knee angles had a weak positive correlation with speed and a weak negative correlation with stride frequency, indicating that the stance phase shortens at higher stride frequencies, resulting in less knee flexion during stance (25). An increase in knee flexion with an increase in speed has been shown previously (26) and might be caused by higher forces on the body that need to be absorbed at higher speeds. The average increase in maximum stance phase knee flexion of 0.8° for every 1 km/h increase in speed is similar to previous findings in controlled settings (0.7°) (26). Maximum stance phase knee flexion angles corrected for changes in speed and stride frequency reveal a significant increase between the first and third stages of the marathon that is not present in uncorrected values. Although a statistically significant difference was found after correcting maximum stance phase knee angles for subject-specific effects of speed and stride frequency, the sample size was small with large variability and the clinical relevance of this finding might be limited. Further research should investigate the effect of speed and stride frequency on knee angles in more runners to investigate the clinical relevance and repeatability of this finding. However, an increase in maximal stance knee flexion could indicate an increase in stride length (60), knee extensor strength loss, or a reduced tolerance to imposed stretch loads with fatigue (44, 61). Despite relatively small explained variances of regression equations for knee angles, subject-specific corrections for changes in speed and stride frequency on knee angles significantly influenced the interpretation of mechanical changes during a marathon.

4.4. Fatigue

Subjects likely experienced high levels of fatigue toward the end of the marathon. Running-induced fatigue typically increases PTA (12), knee flexion at initial contact (12) and tends to increase maximal stance phase knee flexion (52, 57, 62). Both speed and fatigue have been positively associated with PTA and maximum stance phase knee angles (8, 12, 26, 52). Fatigue might have caused lower speed coefficients for PTA and maximum stance phase knee angles than expected without the influence of fatigue. Since subjects generally ran slower at the end of the marathon, PTA and maximum knee angles possibly decreased less with a decrease in speed towards the end of the marathon due to fatigue. Therefore, the influence of speed and stride frequency on running mechanics in an uncontrolled environment might be larger than shown in this study. To omit the effect of fatigue, we could have taken data from the start of the marathon, defined linear regression equations from data in an unfatigued state, and applied a correction to the remainder of the data, similar to Clermont et al. (63). However, most runners will experience some level of fatigue during their runs, making relationships solely based on unfatigued data invalid. Hence, we deliberately included data from an unfatigued to a fully fatigued state to create subject-specific relationships with better ecological validity.

4.5. Limitations

Collecting data in an uncontrolled environment is both a benefit and a shortcoming of this study. The benefit is that runners were measured in the actual environment where they typically run without any constrictions that a laboratory setting or a treadmill would impose on their gait pattern. However, we investigated the effects of speed and stride frequency on multiple mechanical quantities. At the same time, many other external influences could have played a role, such as running surface, fatigue, other runners, or distractions. The explained variance of quantities of interest can be improved by incorporating additional variables into the regression equation. However, for the scope of this paper, we were only interested in how much of the variance in included quantities could be explained by changes in speed and stride frequency.

The limited number of subjects in this study might have led to an underpowered group-based analyses to compare the effect of marathon stage on both corrected and uncorrected PTA and knee angle values. However, the large variability between runners, as demonstrated in the running speed, and speed coefficients for PTA and knee angles, emphasized the need for subject-specific analysis and corrections of the gait pattern, as demonstrated in this research.

Measurement equipment could have influenced the findings of this study in multiple ways. Different sports watches were used which could result in varying sampling frequencies and accuracies of the measured running speed. A lower sampling frequency could lead to allocation of varying PTA or knee angle values to a single running speed or stride frequency, therefore influencing the speed and stride frequency coefficients. Additionally, a low sampling frequency or GNSS signal loss could lead to high measured running velocities (>20 km/h). These high velocities were deemed unlikely and replaced by spline interpolation, potentially underestimating the actual running velocity. However, by computing quantities over segments of 25 strides, the running speed during each segment was computed based on multiple measurements, decreasing the influence of a low running speed sampling frequency and varying accuracies of sports watches on the outcomes of this study. For future studies we would recommend to compute running speed based on IMU signals.

Furthermore, PTA was measured with an IMU fixed to the skin. Skin-mounted IMUs are prone to soft-tissue artefacts as they can move with respect to the underlying bone, resulting in measurement errors (8). IMU displacement with respect to the body could have occurred due to sweating which would have influenced the sensor-to-segment calibration and output of the IMUs. However, IMUs seemed to be properly attached after the marathon and no sudden changes of a sensor becoming loose were found in the data.

4.6. Practical implications

This study showed that running speed and stride frequency have a subject-specific relationship with PTA, knee angles at initial contact, and maximum stance phase knee flexion. Correcting for these relationships influences the interpretation of changes in mechanical quantities while running in an uncontrolled environment and allows for comparisons of mechanical quantities between runs at different running speeds. Many wearable devices provide feedback on peak accelerations to improve the gait pattern (29–31). Typically, feedback is provided on PTA values above a certain generic threshold. PTA values above this threshold which are caused by an increase in running speed or a decrease in stride frequency provide information about the absolute PTA value. The absolute PTA value can easily be lowered by changing running speed or stride frequency. In addition, speed and stride-frequency corrected PTA values provide information about relative PTA values. Speed and stride frequency corrected PTA values that are higher than expected at the current speed and stride frequency can warn runners for suboptimal changes in their gait pattern. Hence, changes in speed and stride frequency corrected PTA values provide information about a shift in the human body while performing a similar task (i.e., running at the same speed with the same stride frequency). A subject-specific model of the relationship between speed, stride frequency and quantities of interest based on multiple runs in different conditions would allow for comparisons of mechanical quantities between runs independent of running speed and stride frequency to better monitor progression of a runner. While this study demonstrated the effect of subject-specific corrections on PTA and knee angles, similar corrections can be made for other quantities of interest. For instance for biomechanical risk factors for overuse injuries like knee stiffness, peak hip adduction, ankle eversion or pelvic drop angles (7, 64, 65). Hence, we advise investigating and correcting for subject-specific regression equations for all quantities of interest when measuring, comparing and providing feedback on running mechanics in an uncontrolled environment.

Conclusions

In this study, we quantified and corrected for the subject-specific effect of changes in running speed and stride frequency on impact-related running mechanics during a fatiguing outdoor run. Subject-specific corrections through multiple linear regression equations revealed a significant effect of marathon stage on maximal stance phase knee flexion, which was previously masked by changes in speed and stride frequency. The effect of marathon stage on PTA and knee angles at initial contact changed after correcting for changes in speed and stride frequency. Hence, speed and stride frequency influence the interpretation of changes in mechanical quantities in a subject-specific manner when running in an uncontrolled environment. Subject-specific effects of speed and stride frequency on quantities of interest should be investigated and corrected when interpreting, or providing feedback on, running mechanics in an uncontrolled environment.

Data availability statement

The accompanying dataset for this study is publicly available. This data can be found here: https://doi.org/10.6084/m9.figshare.22331686.v1.

Ethics statement

The studies involving human participants were reviewed and approved by Ethics Committee Computer and Information Science of the University of Twente. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

JB, PV, and JR were involved with funding acquisition. MZ, JB, PV, and JR all contributed to the design of the study. MZ and JR organized and performed the measurements. MZ performed data analysis. MZ, JB, PV, and JR interpreted the findings. JB, PV, and JR supervised the project. MZ and JR wrote the first draft of the manuscript, after which the manuscript was critically reviewed, edited, and approved by all authors (MZ, JB, PV, and JR). All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY
Steven van Andel,
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REVIEWED BY
Thomas Baxter McGuckian,
Australian Catholic University, Australia
Catherine M. Capio,
The Education University of Hong Kong,
Hong Kong SAR, China

*CORRESPONDENCE
Jonathan Leo Ng,
jonathan.leo.ng@rmit.edu.au

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Construct validation of a general movement competence assessment utilising active video gaming technology

Jonathan Leo Ng[1]* and Chris Button[2]

[1]Department of Health, Physical Education, and Sport, School of Education, College of Design and Social Context, RMIT University, Melbourne, VIC, Australia, [2]School of Physical Education, Sport, and Exercise Sciences, Division of Sciences, University of Otago, Dunedin, Otago, New Zealand

Introduction: The assessment of children's motor competence is an important concern as physical inactivity has been linked with poor movement quality and aspects of well-being such as low self-esteem. The General Movement Competence Assessment (GMCA) is a new instrument that was developed using active video gaming technology.

Methods: Confirmatory factor analysis was conducted to examine the internal validity of the GMCA in a sample of 253 typically developing children (135 boys and 118 girls), aged 7–12 years old (9.9 ± 1.6 years). Further, a second-order confirmatory factor analysis examined how the four constructs fit onto the higher-order variable of movement competence.

Results: Results revealed that the first-order four-construct model of the GMCA was a good fit (CFI 0.98; TLI 0.98; RMSEA 0.05). The second-order confirmatory factor analysis revealed that the four constructs loaded directly onto movement competence. It accounted for 95.44% of the variance which is approximately 20% more than the first-order model. The internal structure of the GMCA identified four constructs of movement competence (i.e., stability, object-control, locomotion and dexterity) based on the study sample.

Discussion: Performance trends in the general movement competence assessment support empirical evidence that movement competence improves as children age. Results suggest that active video games have considerable potential to help assess general motor competency in the wider population. Future work may consider the sensitivity of motion-sensing technologies in detecting developmental changes over time.

KEYWORDS

dexterity, ecological dynamics, children, motion sensing, motor competence

Introduction

Compared to recent generations, 21st-century children have lower levels of movement competence (Hardy et al., 2013; Tester et al., 2014). We define movement competence as the capacity of an individual to adapt movements based upon affordances and action capabilities to produce goal-directed movement solutions that are effective and efficient. The functionality of emergent movement solutions arises from a group of inter-related constructs (such as balance, posture, and coordination). Evidence suggests that children that move competently are more likely to stay engaged in physical activity throughout their lives (Stodden et al., 2008; Lubans et al., 2010; Logan et al., 2014; Logan et al., 2015; Barnett et al., 2016). Yet it is concerning that there are increasing levels of sedentary behaviour and physical inactivity in children (Hallal et al., 2012; Farooq et al., 2018).

Video games have garnered much interest in the scientific community in the last decade as an alternative approach to getting children more physically active due to their mass appeal (LeBlanc et al., 2013). Active video games (AVGs) rely on motion-sensing technology to track the body movements of participants. These tracked movements are presented on a screen and embedded in progressions within the game. In particular, AVGs have been suggested as potential alternatives for monitoring and assessing movement competence (Giblin et al., 2014; Hulteen et al., 2015; Guess et al., 2017). Moreover, playing video games has been purported to solicit high levels of engagement, enjoyment and motivation (Hulteen et al., 2015; Lorenz et al., 2015; Smits-Engelsman et al., 2017).

A popular AVG system is the Microsoft Xbox 360 which utilises the Microsoft Kinect sensor (Microsoft, 2022) for motion detection. Studies involving the use of AVG systems such as the Microsoft Kinect have focused on its utility to monitor specific limb-joint movements (Choppin et al., 2014; Seo, Fathi, Hur, & Crocher, 2016; Napoli et al., 2017) and feasibility of its use as a rehabilitative tool (Camara Machado et al., 2017; Page et al., 2017). The Microsoft Kinect has been proven as a valid and reliable tool for use in tracking specific joint movements (Choppin et al., 2014; Guess et al., 2017; Napoli et al., 2017) as well as whole body movements (Hulteen et al., 2015; Guess et al., 2017).

AVGs for assessing movement

The theoretical framework underpinning the development of the GMCA is ecological dynamics. The theory suggests that movement responses are a consequence of the dynamic interactions between individual, task and environmental constraints (Newell et al., 1991) that are scaled based on the affordances (or opportunities to act) and action capabilities of the individual (Dicks et al., 2009; Button et al., 2020). Thus, a wide variety of movement experiences and exploration in movement contribute to greater movement competence (Seifert et al., 2013; Rudd et al., 2020a). As a child ages, the compounding effect of movement experiences accumulates and progressively, the child becomes more competent in movement (Clark & Metcalfe, 2002). They become more sensitive to the affordances and are thus better able to adapt movement solutions based on their action-capabilities. In other words, movement competence is age-related and dependent on engagement in varied movement experiences.

Movement competence is typically assessed with movement assessment batteries (MABs) evaluating performance across three constructs; stability, locomotion and object-control (Gallahue & Ozmun, 2006; Barnett et al., 2016). The stability construct includes movements that emphasize balance in static and dynamic situations which require coordination of the trunk and axial limb movements. Specific examples can include balancing on one foot statically or dynamic forms such as walking along a line. The locomotion construct includes movements that allow body transportation from one point to another, such as sliding, leaping and galloping. The object-control construct describes manipulative, interceptive and prehension movement types such as catching, throwing or striking with and without additional equipment such as gloves or rackets and tools such as hammers. It typically involves the transmission of force to manipulate, move or receive an object.

MABs would often measure movement competence by evaluating combinations of or all of the three constructs. The origin of MABs have a clinical origin and they were purposefully designed to identify children with poor competence who would potentially require clinical intervention. These batteries however remain commonly used in the general population as a test of general movement competence in research and as an indication of performance in general programmes such as physical education and sports (Cools et al., 2009; Giblin et al., 2014; French et al., 2018). Importantly, the original intent for MABs to identify deviations from typically developing individuals lead to the design of simplified and isolated assessment tasks. This undoubtedly creates a ceiling effect when used with general populations. A ceiling effect is observed when a large portion of the sample attains high scores in a test resulting in a skewness in statistical analyses. It indicates that a test is not challenging enough for the specific cohort. Hence, in the context of MABs, the presence of ceiling effects in some MABs indicate a lesser sensitivity at identifying individuals who are performing at the higher end of the movement spectrum (French et al., 2018).

These MABs tend to involve the observation of discrete tasks that are often sport-related (such as balancing, running, jumping, throwing and striking) in tightly regulated settings (Cools et al., 2009; Ng & Button, 2018). The tasks common to these MABs are performed in isolation and often stripped of context to promote reliability (e.g., performing a static dribble as compared to dribbling in an actual physical activity and/or sport-orientated setting) (Pinder et al., 2011). The decontextualized design of these activities results in assessment tasks that are over-simplistic and prone to bias from cultural differences between countries (Cools et al., 2009). This can result in unfair bias against children that may have not had the same opportunities to participate in sports and certain physical activities that involve the use of the assessed movement skill (Rudd et al., 2020b; Smits-Engelman et al., 2022). Essentially, these MABs are being used for purposes that they were not originally designed for.

Process and product-based assessments primarily differ in assessment forms. Process-based assessments utilise observational criteria to determine the quality of a particular movement (e.g., running form) that are criterion-referenced. Product-based assessments measure quantitative, outcome variables (e.g., running duration) and are often referenced with normative samples. Many MABs adopt criterion-based reference in evaluating movement competence by comparing the performances of individuals based on the 'correctness' of the technique employed in specific tasks (e.g., how to throw or catch a ball). In order to reliably reproduce the assessment settings, MABs are composed of static and isolated tasks that downplay or remove typical affordances that are present in a naturalistic setting (e.g., throwing a pass to an unmarked team-mate in a game situation). The technique-focused outcome typically requires a specific set of desired movement solutions (Kane, 2013). Hence, individuals who may be successful in achieving outcome goals through alternative, innovative forms of movement are penalised. Arguably, the assessment tasks do not allow children to demonstrate their ability to react and respond to changing constraints that are typical in an authentic setting (Newell et al., 1991; Cools et al., 2009).

In recent times, some contemporary MABs have begun adopting a more purposeful approach in the design of assessment tasks as a consequence of growing concerns about their ability to distinguish between more or less competent individuals. These validated MABs include more dynamic tasks such as obstacle courses and game-based formats to evaluate movement in more representative contexts (e.g., Tylor et al., 2018; Flôres et al., 2021; Morley et al., 2021).

In our opinion, the game-based virtual environment of AVGs has considerable potential in offering a dynamic environment within controlled settings to potentially evaluate movement competence. Physical interaction with AVGs allows individuals to demonstrate their ability to accurately scale movement responses based on the changing affordances presented in modifiable tasks. Notably, the use of motion-sensing video game technology would ease some logistical constraints of space and equipment (e.g., typical requirements of MABs are large, unobstructed rooms such as school gyms) as well as the need for specialised training and assessors required by many MABs (Cools et al., 2009; Giblin et al., 2014). As gaming and e-sports continue to grow in popularity around the world (Franks et al., 2022), an active gaming platform may offer an inclusive means to develop general movement competency assessments that are less sensitive to cultural differences.

A new movement assessment instrument, the General Movement Competence Assessment (GMCA) was developed using the technology of the Microsoft Kinect with a series of AVGs created to assess various attributes of movement. In a previous study, Ng and others (2020) proposed the inclusion of a new movement construct (i.e., dexterity) in addition to the three commonly accepted constructs of movement competence (i.e., stability, locomotion and object-control) to provide a more encompassing description of movement competence suitable for the general population of healthy children. Before this work, dexterity had not been previously identified as an interdependent construct in the model of movement competence. Although the exploratory factor analysis showed that over 70% of the variance in performance on the GMCA games was explained by a four-construct model, a cautious approach was taken in generalising results with a limited sample size of 83 children (aged 8–10 years). This prompted further validation work with a focus on increasing sample size across wider age groups.

Robust assessments of children's movement competency are of fundamental importance given the potential impact on health given declining levels of physical activity globally. Unfortunately, many existing movement assessment tools that were designed to classify children with very low competency over-emphasise technique instead of adaptation to constraints as well as creative movement alternatives to overcome movement problems. We propose that AVGs offer a promising platform to develop a new movement competency assessment tool that is suitable for use in the general population of children. The primary aim of the present study was to assess the internal structure of the GMCA in a sample of children 7–12 years old through confirmatory factor analysis of the proposed four-construct model consisting of dexterity, stability, locomotion and object-control (Ng et al., 2020).

Materials and methods

Participants

The study sample consisted of 259 typically developing children, ranging from 7–12 years of age (*M* age = 9.97 years, *SD* = 1.61) from a variety of ethnicities. There were 138 boys (*M* age = 10.12 years, *SD* = 1.57) and 121 girls (*M* age = 9.80 years, *SD* = 1.64). All children were recruited through a convenience sampling method from a public primary school in Dunedin, New Zealand. As the GMCA had not been programmed to accommodate individual differences for children with disabilities, children with any physical impairment or disabilities (e.g., visual, hearing impaired, children with cerebral palsy, etc.) were excluded from the study. Written informed consent was attained from both parents and child participants and approval for the study (17/071) was obtained from the Human Ethics Committee of the participating institution.

Simulation work suggest that sample sizes for confirmatory factor analysis with maximum likelihood varies. Jak et al. (2014) classify sample sizes of $n \leq 250$ as "small". However, power estimates conducted for this study suggested sample sizes of between 200–300 for the test of closeness of fit (PCLOSE) for values of 0.769 and 0.928, respectively (MacCallum et al., 1996). Additionally, considering the degrees of freedom (*df*) for the extracted four-construct model of Ng et al. (2020) the sample size (n = 259) for the study was suitable based on the recommendations of MacCallum and others (1996) and fits the recommendations of other simulation work (Marsh et al., 1988; Kim, 2005; Wolf et al., 2013).

The GMCA application

The GMCA is a custom-written application (programmed in C++) that utilises the open-sourced Kinect for Windows Software Development Kit 2.0 to work with the Microsoft Kinect 2.0 system (Microsoft, Redmon, WA). The Kinect system consists of an infrared emitter, colour video and depth sensor. It tracks movements from the reflection of emitted infrared rays. The video and depth sensor captures three-dimensional movements and automatically locates and detects 25 joint centres of the human body.

The GMCA consists of five custom-programmed active video 'games'. The five games are called *Balance, Precision, Control, Swiftness*, and *Interception*, with each game increasing in task difficulty as one meets the movement demands required by each stage (see Supplementary Table S1). The order of the various GMCA games were presented as follows[1]: 1) Precision_unimanual, 2) Balance, 3) Precision_symmetrical, 4) Control, 5) Swiftness, 6) Precision_asymmetrical and 7) Interception. Once started the

1 The order of GMCA games could be manually chosen if needed. The default sequence of the GMCA broke up the various stages of the Precision game in order to prevent fatigue in the arms. These broken up stages were ordered progressively with increasing difficulty.

games would run automatically without the need for external administrators. Performance scores for each task were calculated based on how well children completed (or not) the progressively difficult levels of each game. Thus, if an individual did not do well in earlier stages of the game it was expected that they would not be as accomplished in the later stages.

The spatiotemporal demands of each task were pre-programmed into the software and these were modified to increase once a participant reached a specified threshold of achievement. Thus, the relative demands placed on the individual in terms of difficulty and complexity increased at each stage (e.g., the game *Precision* started with symmetrical pathways to asymmetrical pathways resulting in an increased difficulty and complexity of the task). Hence, individuals had to adapt their movement responses appropriately and it was expected that individuals at the higher end of the movement spectrum (Ng & Button, 2018) would have better performances even in the more complex stages of the games.

Measured variables of GMCA games

The GMCA assesses movement competence based on the measured variables from each game (for details see: Ng et al., 2020). For example, in the *Balance* game, a static balance pose is considered successful when the prescribed hands and feet positions were held for 3 s. The measured variable for *Balance* was the total number of successful poses held for each of the three stages. Importantly, the more competent individual would be better able to adapt the emergent postural control strategies and body configurations to suit the demands of the task. Recorded variables for the game, *Precision*, included the total time taken to move an object around set courses for three levels of difficulty. Measured variables from *Control* included the total number of balls used for the game and the total number of balloons popped. *Control* required individuals to first, juggle a virtual ball on the screen, then manoeuvre the ball to 'pop' a balloon that appeared at random locations on the screen. Hence, a proficient player would be able to control the juggle of a ball and use that same ball to pop the balloons that appeared throughout the game. On the other hand, a less able player would use more balls since a ball was 'replaced' when it was 'lost' (i.e., juggled out of control). Variables from the *Swiftness* game included the total amount of time taken to move between set places in the play area for each of the two levels of difficulty. Finally, the game, *Interception*, required participants to primarily, 'save' spaceships by hovering a hand over them as they appeared at randomised locations on the screen at the same time. A secondary task required participants to 'intercept' stray asteroids by touching them using the other free hand. The asteroids were programmed to take random flight paths and fly at random speeds throughout the game. The measured variables for *Interception* were the number of spaceships 'saved' and the number of spaceships 'lost' (or destroyed by the stray asteroids).

Equipment and test layout

The standing height and weight of participants were measured with a portable stadiometer and a digital scale (UC-321, A&D Company Limited). The GMCA games were displayed on a Sony KDL-40EX400 40-inch 1,080 pixels HDTV. The TV was set upon a standing console 0.8 m from the ground. The Kinect Sensor was placed directly in front of the TV facing the game area. All trials were recorded to serve as a reference in the event of discrepancies.

In the present study, the game area measured 2.05 by 2.55 m. The distance between the Kinect sensor and the game area measured 2 m away from the front edge of the Kinect sensor to the front boundary of the play area. Play area boundaries were marked out with high-contrast coloured tape on the ground.

Procedure

Participants' anthropometric measures were recorded 1 week before data collection. Age was calculated by subtracting the date of the testing date from the birth date of each child. The start and end of the GMCA application were controlled by an experimenter operating the computer at each testing station. The GMCA does not require any specialised training, nor does it require the presence of a tester with specialised knowledge of motor performance for the GMCA was programmed to run automatically. All participants engaged in the GMCA trial once immediately after their familiarisation trial. Including familiarisation, the entire GMCA test duration ranged from approximately 10–18 min per individual. More competent individuals completed GMCA trials faster[2].

Data analysis

Internal consistency

Data were analysed using the Statistical Package for the Social Science (SPSS; version 24, IBM Corp., Armonk, NY) with statistical significance set at $p \leq 0.05$. To determine the degree of homogeneity of measured variables from each movement construct of the GMCA, internal consistency reliability was analysed by omega coefficient; ω (McDonald, 1999). Reliability was accepted at $\omega > 0.7$ (Nunnally & Bernstein, 1994).

Confirmatory factor analysis

A proposed four-construct model of the GMCA was validated for the study sample using confirmatory factor analysis. To determine the suitability of the data for factorial analysis, data were screened using Kaiser-Meyer-Olkin (KMO) and Bartlett's test of sphericity. Data is suitable for factor analysis when the KMO value is more than 0.6 (Kaiser & Rice, 1974) and when Bartlett's test is significant ($p < 0.05$). When assumptions were met, confirmatory factor analysis was conducted using the maximum likelihood method of estimation in AMOS 24.

The fit of the tested model was interpreted from various fit indices. On top of the chi-square ($\chi 2$) statistic and df, other

2 More competent individuals recorded faster completion time for GMCA games such as Precision and Swiftness were time based. Hence, more competent individual completed those games faster, thus, resulting in faster overall completion times.

goodness-of-fit indices were used to determine model fit. These were the χ2 divided by the df (χ2/df), Comparative Fit Index (CFI; Bentler, 1990), Lewis-Tucker Index (TLI; Tucker & Lewis, 1973), root mean square of approximation (RMSEA; Steiger & Lind, 1980; Browne & Cudeck, 1993) with confidence intervals (CI) and probability of the test of close fit (PCLOSE; Hu & Bentler, 1999).

The χ^2 statistic measures the overall fit of the model with a higher probability ($p > 0.05$) indicating a closer fit between the tested model and the perfect fit (Bollen, 1989). Instances of good fitting models being rejected with the test of exact fit due to the large χ^2 statistic relative to the *df* have been highlighted in the literature (Jöreskog & Sörbom, 1993). Thus, other alternative indices of fit were used to address the limitations associated with the χ^2 statistic.

Alternate fit indices (i.e., χ^2/df, CFI, TLI and RMSEA) are typically used as adjuncts to the χ^2 statistic. χ^2/df provides an indicator of fit with values of less than 2 being considered an adequate fit (Wheaton et al., 1977). The CFI is a revision of the Normed Fit Index (NFI; Bentler & Bonnet, 1980) that takes sample size into account since a limitation of NFI is the underestimation of fit in small samples (Byrne, 2013). The TLI yields values from 0.0 to 1.0. Values closer to 1.0 are indicative of a good fit. CFI and TLI values more than 0.9 were interpreted as "acceptable", while values more than 0.95 were "good" (Hu & Bentler, 1999).

The next fit statistic, RMSEA, is postulated to be one of the most informative fit indexes as it considers the error of approximation through the provision of CIs (Browne & Cudeck, 1993). RMSEA values of less than 0.05 are indicative of a "good" fit; 0.05 to 0.08, "fair" and 0.08 to 0.10, "mediocre" (Browne & Cudeck, 1993). Nonetheless, Hu and Bentler (1999) propose that RMSEA values of up to 0.06 can still be considered a good fit. CI substantiates the RMSEA value by providing additional information regarding the precision of estimates (MacCallum et al., 1996). For example, if the lower bound of the RMSEA's CI is above 0 and less than 0.05, then the probability of the χ^2 statistic being less than 0.05 is expected (MacCallum et al., 1996). Additionally, if the upper bound of the CI is above 0.05, it would be an indication of a plausible good-fitting model.

PCLOSE is a test for the closeness of fit. Specifically, it tests the hypothesis that the RMSEA value is "good" for the sample population. The probability for the PCLOSE test should be $p > 0.50$ (Browne & Cudeck, 1993).

The four-construct model of the GMCA was validated in this population of children aged 7–12 years old. Modification indices generated by AMOS 24 were only considered if proposed modifications were theoretically grounded, else, modifications made would reflect minute changes in the model according to the nuances of the sample (Byrne, 2013). In addition, a second-order confirmatory factor analysis was conducted to examine if the four constructs loaded onto the higher-order variable of movement competence.

Results

Internal consistency

Preliminary examination confirmed there was no significant difference in age within the sample for boys and girls ($p = 0.11$). Table 1 shows the results of the internal consistency reliability analysis for each of the four constructs measured by the GMCA.

TABLE 1 Internal consistency reliability of the four GMCA constructs.

Construct	Variables included	Omega coefficient
Stability	Balance stage 1	0.74
	Balance stage 2	
	Balance stage 3	
Dexterity	Spaceships stage	0.96
	Spaceships lost	
Locomotion	Swiftness stage 1	0.87
	Swiftness stage 2	
Object-control	Balls used	0.87
	Precision stage 1	
	Precision stage 2	
	Precision stage 3	

For all constructs, omega coefficients were above the recommended 0.7 value.

Confirmatory factor analysis

Confirmatory factor analysis with maximum likelihood estimation was conducted to test the internal structure of the GMCA as extracted from a previous study (Ng et al., 2020). Assumptions testing indicated that the sample data was suitable for factorial analysis. The KMO value was 0.86 which indicated excellent suitability and Bartlett's test was significant ($p < 0.001$).

The path diagrams (i.e., Figures 1–3) of confirmatory factor analysis comprise all 11 measured variables included in the analysis as well as the four specified constructs of the GMCA. Each construct consists of the measured GMCA game variables (also known as observed variables) and is influenced by a random measurement error, indicated by the associated error term (e.g., e1, e2, e3, etc.). Each observed variable regresses onto its respective construct. Finally, the constructs co-vary *via* the corresponding covariate arrows in path diagrams from the specified model.

First-order factor analysis for the four-construct model of the GMCA

The specified model (Model 1; see Figure 1) was based on the four-construct model extracted from the exploratory factor analysis of Ng and others (2020). The four constructs measured were balance, locomotion, object-control and dexterity. The variable, Balance Stage 1, was specified to double load onto the locomotion construct as dynamic balances are proposed to influence the performance of locomotion tasks (Bril & Brenière, 1993).

The initial confirmatory factor analysis for the specified four-construct model (Model 1; see Figure 4.2) found an adequate fit ($\chi^2(37) = 60.006$; $p = 0.010$; $\chi^2/df = 1.622$; CFI = 0.988; TLI = 0.983; RMSEA = 0.049, CI 0.024–0.071; PCLOSE = 0.500).

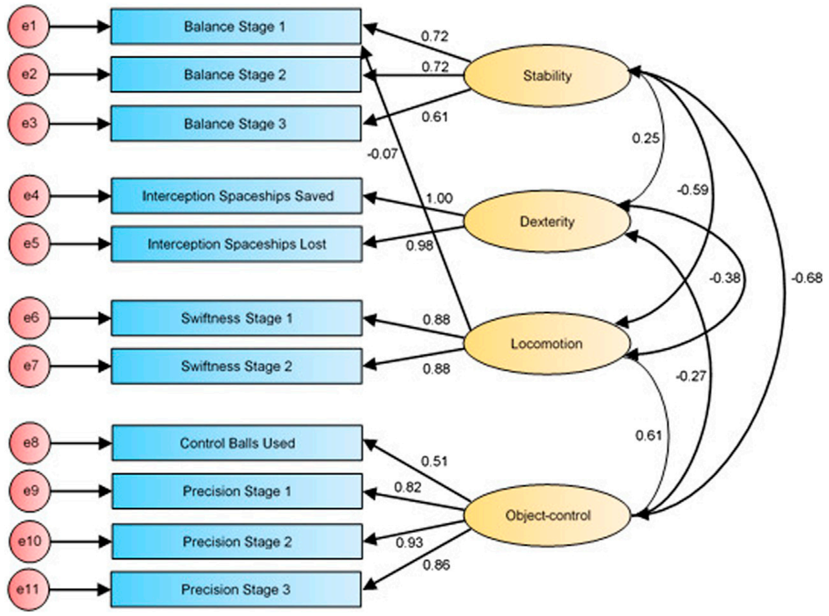

FIGURE 1
First-order factor structure of the GMCA (initial fit; Model 1).

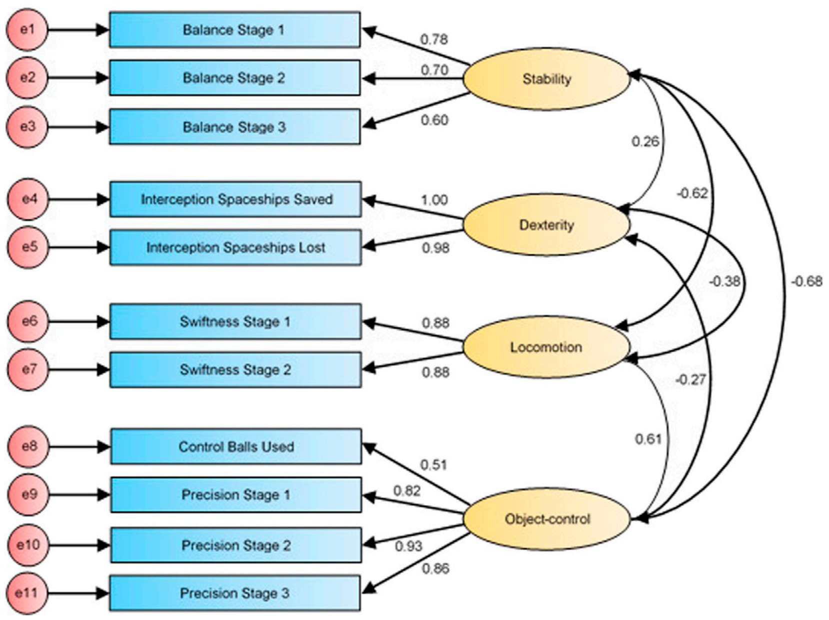

FIGURE 2
First-order factor structure of the GMCA (re-specified fit; Model 2).

In model 1, the standardized regression weight of Balance Stage 1 loading onto the locomotion construct was −0.072. Notably, factor loadings (i.e., regression weight) of less than 0.4 are not considered valuable to the overall model fit (Sireci, 2007). Thus, the initial model (Model 1; see Figure 1) was re-specified with the removal of the double loading between Balance Stage 1 and the locomotion construct and confirmatory factor analysis was conducted again.

The second model (Model 2; see Figure 2) supports the data characteristics well based on fit indices ($\chi^2(38) = 60.588$; $p = 0.011$; $\chi^2/df = 1.594$; CFI = 0.989; TLI = 0.983; RMSEA = 0.048, CI

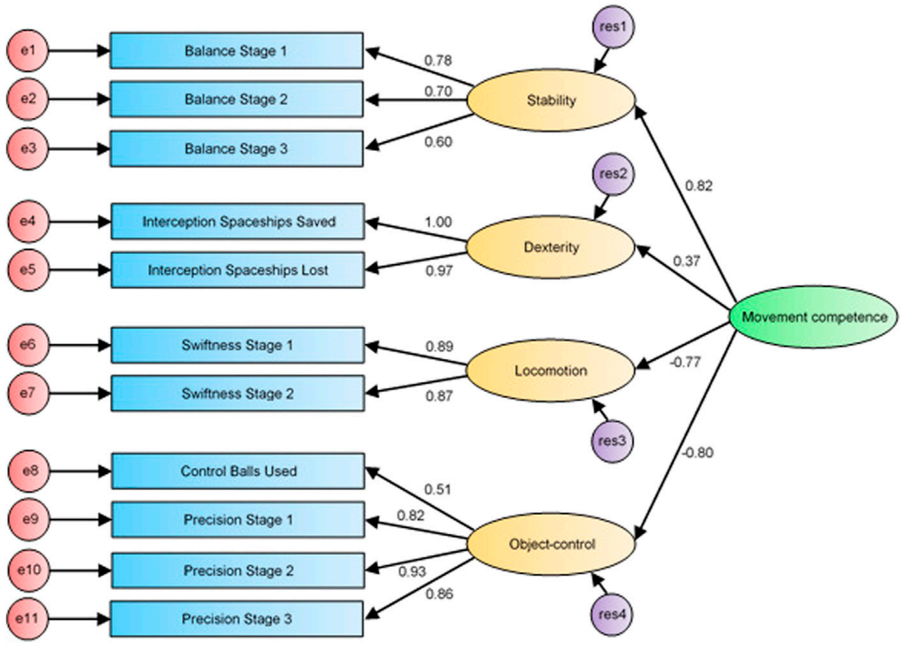

FIGURE 3
Second order CFA model for movement competence.

TABLE 2 Fit indices of each specified model.

Model	Description	χ^2	*df*	*p*	χ^2/df	CFI	TLI	RMSEA [CI]	PCLOSE
1	Hypothesized four-construct model	60.01	37	0.01	1.62	0.99	.98	0.05 [0.02, 0.07]	0.50
2	Four-construct model without double loading	60.59	38	0.01	1.59	0.99	.98	0.05 [0.02, 0.07]	0.53
3	Movement competence model	67.38	40	0.00	1.68	0.99	.98	0.05 [0.03, 0.07]	0.43

Abbreviations: χ^2, chi-square; *df*, degrees of freedom; *p*, probability; CFI, comparative fit index; TLI, Lewis-Tucker index; root mean square of approximation, RMSEA; CI, confidence interval; PCLOSE, probability of the test of close fit.

0.023–0.070; PCLOSE = 0.533) which accounted for 74.85% of the variance. Modification indices suggested several ways to enhance the model fit, however, the suggested changes were not theoretically justifiable.

Second-order factor analysis for movement competence

With the first-order confirmatory factor analysis establishing a good fit of the specified four-construct model of the GMCA, a second-order confirmatory factor analysis was undertaken that specified for each construct to load onto the higher-order variable of movement competence. The four second-order latent variables of stability, dexterity, locomotion and object-control were specified to load directly into movement competence (see Figure 3).

Results indicated that an adequate fit was achieved ($\chi^2(40)$ = 67.376; $p = 0.004$; $\chi^2/df = 1.684$; CFI = 0.986; TLI = 0.981; RMSEA = 0.052, CI 0.029–0.072; PCLOSE = 0.429) and accounted for 95.44% of the variance (approximately 20% more variance than the first order model accounted for). Table 2 provides a tabled comparison of the various fit indices for the three tested models.

Discussion

The present study examined the internal structure of the GMCA. Both the first and second-order confirmatory factor analysis models indicated a good fit, particularly to the sample data. The specified internal structure of the GMCA, existing as a four-construct model was empirically supported. These results confirm that the GMCA is a multi-dimensional assessment and that all four constructs have varying degrees of influence on the description of movement competence. The findings supplement previous studies that have highlighted the interdependence between movement constructs (Bril & Brenière, 1993; Davids et al., 2000; Rudd et al., 2016). Consequently, all constructs that defined it should ideally be considered when evaluating the general movement competence of typically developing individuals. This may suggest the need to supplement MABs that measure three specific movement constructs (e.g., locomotion, object-control and stability) with other forms of assessment to gain a better description of general movement competence, especially in typically developing populations.

Importantly, the model confirmed that another movement construct (i.e., dexterity) is required to differentiate the movement competence of children of different ages. Results of confirmatory factor analysis for the GMCA game variables loading onto the construct of dexterity provide a working definition for dexterity as the act of using/moving both sides of the body independently, in order words, the ability to be competent bilaterally (including bimanual coordination). Indeed, some MABs include dexterous tasks that require successful coordination of both sides of the body to achieve outcome goals (e.g., Bruininks-Oseretsky Test of Motor Proficiency second edition (BOTMP-2); Bruininks, 2005). However, dexterity has not yet been identified as an independent construct of movement competence nor included as an independent construct in other validated MABs. For example, results for the dextrous tasks loaded onto the construct defined as gross motor skill construct in BOTMP-2 (Bruininks, 2005).

With our definition of movement competence, the inclusion of dexterity as an additional construct in the model of movement competence may provide supplementary evidence for the traits of competent individuals and better distinguish between individuals residing across the movement competence spectrum. Additionally, evaluating dexterity can potentially supplement MABs that examine other commonly accepted constructs of movement (e.g., stability, locomotion and object-control; Gallahue & Ozmun, 2006). This would also respond to previous recommendations calling for MABs to be supplementary to each other (Cools et al., 2009; Rudd et al., 2015).

For the version of the GMCA used in this study, the Balance game was updated to only include one-leg balances as compared to a mix of two- and one-leg balances for an earlier version of GMCA (Ng et al., 2020). In the extracted model from Ng and others (2020), the one-leg balance variable is loaded onto the locomotion construct. Hence, an exact replica of the model would mean that all the Balance variables (from the updated version of GMCA) would need to be specified to co-vary with the locomotion construct. Had this been done, it would be akin to specifying that the stability and locomotion construct co-vary which confirmatory factor analysis procedures by default requires (i.e., all constructs of specified models must co-vary). Thus, as the model (see Figure 2) was already specified to co-vary between the stability and locomotion construct, the double loading of Balance Stage 1 to the locomotion construct was redundant (Brown, 2014). In model 2 (see Figure 2), the double loading of Balance Stage 1 was removed which resulted in a marginally better fitting model. Large improvements to the model after re-specification was never expected since the double loading only had a negligible standardised regression weight of −0.072. Hence, a slight improvement in the model fit was expected with this modification.

The second-order confirmatory factor analysis model (see Figure 3) revealed that the construct with the strongest correlation with movement competence was stability (r = 0.82). This strong association was closely followed by the object-control (r = −0.80), and locomotion (r = −0.77) constructs, and then by dexterity (r = 0.37). Although the dexterity construct was found to load the weakest (r = 0.37) onto movement competence, it still makes an important contribution to the overall model fit. The dexterity construct was made up of variables from the Interception game which measured the ability of individuals to use both sides of their body independently to achieve outcome goals. Findings from Rudd and others (2016) indicate the coordination construct was made up of assessment tasks from the Körperkoordination Test für Kinder (Kiphard & Schilling, 2007) that focuses on bilateral coordination competence. Hence, despite the weak loading, it is suggested that the role of dexterity should not be neglected for its role in describing general movement competence (Bernstein, 1996).

Individuals at the higher end of the spectrum may be more proficient at dexterous tasks based on their varied movement experiences in relation to the movement dynamics (Bernstein, 1996; Logan et al., 2014; 2015; Morley et al., 2021). From an ecological dynamics perspective, engaging in an enriched environment provides for varied movement experiences (Ng and Button, 2018; Scheuer et al., 2019; Button et al., 2020). These remain critical for individuals in all life stages since the varied movement experiences would increase an individual's sensitivity to their action capabilities (Clark & Metcalfe, 2002; Hulteen et al., 2015). An individual's increased awareness of action capabilities also decreases the risks for potential injury since the varied movement experiences contribute to an increased sensitivity to the affordances or "opportunities to move". Importantly, varied movement experiences allow the emergence of dexterous movements to be developed and refined (Bernstein, 1996) which may suggest that individuals who have had a wider range of movement experiences may also reside at the higher end of the movement spectrum. Thus, the finding of dexterity as a construct of movement competence is significant.

Lastly, the results of the present study indicate that stability remains the most influential construct of movement competence. Compared to the other constructs, stability explained the largest percentage of variance (20.5%) from the exploratory factor analysis conducted by Ng and others (2020). Notably, previous studies highlighting the importance of stability competence on other movement constructs have advocated strongly for its inclusion in movement competence assessments (Davids et al., 2003; Luz et al., 2016; Rudd et al., 2016; Anderson, Button, & Lamb, 2022).

Assessment form

To measure movement competence, process-based assessment approaches have been recommended (Ulrich, 2000; Stodden et al., 2009). Indeed, the GMCA utilises a product-based approach towards the measurement of movement competence. Process and product-based assessments primarily differ in assessment forms. Although the validity of both forms of assessments to measure movement skills have been raised before (Stodden et al., 2008; Logan et al., 2012), previous studies have suggested associations between the two (Roberton & Konczak, 2001; Miller et al., 2007; Mally et al., 2011), thus, highlighting that both forms have their merits and that results from both assessment forms are valid for the purposes that they were designed for.

From an ecological dynamics perspective, the implications on practice are that learning or assessment tasks in the movement context should in design and execution strive to ensure that the link between perception and action remains and is not left decoupled by design. When assessment tasks are decoupled or decontextualized, it limits the opportunity to provide an accurate description of movement competence. A simulated assessment environment should have elements of the performance environment to ensure representativeness (Chow et al., 2007; Dicks et al., 2009; Pinder et al., 2011). This allows individuals to demonstrate their capacity to adapt efficient movement forms that are self-organised based on inherent individual differences (Schöllhorn et al., 2002) in addition to the demands presented by dynamic movement situations which are found in activities of daily living physical activity and sport at all levels of participation. The effectiveness, efficiency and quality of movement can then be judged based on a contextualised movement problem that keeps the perception-action coupling intact.

Understanding the process of movement or assessing its quality is suggested to be an important feature in determining the efficiency of movement (Ulrich, 2000) and process-based MABs often assess children's movement skills based upon a mature, expert-like form (Stodden et al., 2008). Notably, that approach fails to consider the influence of individual differences on movement responses (Vella et al., 2023). Importantly, variability of and within observed movements is inherently present due to the unique individual differences of every individual (Chow et al., 2007). In addition, there are no universally ideal or expert-like patterns of movement (Davids et al., 2013; Seifert et al., 2013). Hence, the GMCA was developed as a product-based assessment that is concerned with the movement outcome since the process of executing movement would be unique to each individual, based upon their action capabilities and interaction with task and environmental constraints.

Strengths, limitations and future directions

One of the merits of this study is its utilisation of relatively low-cost, portable video game technology that can be operated without specialised training to help ease some of the constraints of current MABs such as the need for trained assessors (Cools et al., 2009). As the GMCA was written with an open-source application, there is potential to further programme customised games that could suit various population samples. There is potential for the GMCA to also be used as a supplementary teaching aid for the general population. There is also considerable promise for the GMCA with its AVG modality to be used in conjunction with intervention programmes for clinical populations (Camara Machado et al., 2017; Page et al., 2017). The large sample of children utilised and naturalistic settings (i.e., in school classes) were also strengths of the study. Notably, our results suggest stability competence has a critical influence on the other three movement constructs which signals future work to establish if the influence is variable across the age groups.

There are some limitations in this study. First, the model fit was specific to the study sample and some caution has to be heeded in generalising to other populations. Future studies should consider its validity in other populations. Assessing validity is an ongoing process of evaluating data that is first derived from a specific population. Hence, more than one source of evidence is necessary (Messick, 1989). Furthermore, as evident in past validation studies of MABs, a critical limitation has been raised concerning the incongruent results found when particular MABs were used in different populations from normative samples (Chow et al., 2006; van Waelvelde et al., 2008; Bardid et al., 2016). Hence, future studies should consider validating the GMCA in other populations to further supplement the validity evidence (Zumbo & Chan, 2014). Secondly, the efficacy of any assessment will be in its discriminative validity to detect changes over time however this was not yet established in this study. Therefore, to further validate the GMCA, future research should determine the GMCA's sensitivity in tracking developmental changes. Lastly, it is also recommended that the relationship between dexterity and overall movement competence be explored further to inform the design of future movement assessments that are suitable for use amongst the general population. Future studies should explore the role of dexterity in distinguishing children across the spectrum of movement competence. This could be achieved through concurrent validation studies between the dexterous tasks of the GMCA and the other validated assessment batteries such as the Brunicks-Oseretsky Test of Motor Proficiency (Bruininks, 2005) and Movement ABC-2 (Henderson et al., 2007).

Conclusion

The validity evidence obtained from this large sample of school children confirms the GMCA measures general movement competence *via* a four-construct model. Importantly, this study reaffirms that dexterity can be considered an independent construct in the model of movement competence (Ng et al., 2020).

The GMCA does not require specialised training, it is relatively easy to use, and it can be adapted for use with other motion-sensing technologies[3] (e.g., Azure Kinect DK, Microsoft, 2023) since C++ is a flexible and adaptable language. In this study, the GMCA utilised the technology of video games to provide interactive dynamic movement assessment tasks. The use of dynamic over static tasks in the GMCA maintains the perception-action coupling which is more representative of how we interact in the real world through movement. Additionally, dynamic tasks allow individuals to demonstrate their ability to adapt and respond to changing task constraints. As a product-based measure, it affords multiple movement solutions to be used instead of focusing on one 'ideal' solution which may not be as inclusive for all due to our unique individual differences and movement preference.

Indeed, the potential to incorporate the use of motion-sensing technology as a novel supplement can complement current methods of assessing movement competence and may prove useful to practitioners in the industry.

3 Microsoft has discontinued manufacturing the Kinect 2.0. However, with C++ as the programming language for the GMCA, the opportunity remains for the application that is also open source to be adapted for use with other commercially available motion-sensing devices.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Human Ethics Committee of the University of Otago. Written informed consent to participate in this study was provided by the participant's legal guardian/next of kin.

Author contributions

JN and CB contributed to conception and design of the study. JN organized the database, statistical analysis, and wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbioe.2023.1094469/full#supplementary-material

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