HEALTH AND PERFORMANCE ASSESSMENT IN WINTER SPORTS

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PUBLISHED IN: Frontiers in Sports and Active Living

frontiers Research Topics

ISSN 1664-8714
ISBN 978-2-88966-720-8
DOI 10.3389/978-2-88966-720-8

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HEALTH AND PERFORMANCE ASSESSMENT IN WINTER SPORTS

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Citation: Aminian, K., Spörri, J., Stöggl, T. L., eds. (2021). Health and Performance Assessment in Winter Sports. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-88966-720-8

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frontiers in Sports and Active Living

EDITORIAL
published: 09 March 2021
doi: 10.3389/fspor.2021.628574

Editorial: Health and Performance Assessment in Winter Sports

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Keywords: algorithms, biomechanics, diagnostics, digital health, injury prevention, performance enhancement, sensors, athlete

Editorial on the Research Topic

Health and Performance Assessment in Winter Sports

Recent developments in technology and engineering have provided novel solutions for monitoring health and performance, as well as assessing key variables that would not have been easily accessible a few years ago. Options include digital solutions for collecting self-reported data on physical activity, recovery, psychological readiness, or injury (Düking et al., 2018), measurement technologies for quantifying physiological variables (Khundaqji et al., 2020), wearable sensors for motion analysis (Sperlich et al., 2020), and technology-based approaches for performance and load quantification (Lutz et al., 2019). Moreover, customized algorithms and data analytics help to extract and visualize relevant metrics for effective coaching and athletes' health protection (Rommers et al., 2020).

A close relationship between engineers, coaches, sports scientists, and medical professionals ensures the success of healthy sporting activity and the sustainable long-term development of athletes throughout their careers. This is especially true for winter sports and youth athletes. On the one hand, the assessment of health and performance in winter sports is a permanent challenge and, from a technological point of view, particularly difficult. Winter sports take place under extreme and hardly standardisable outdoor conditions. Therefore, various research is done in laboratory situations (e.g., ski simulators, ski ergometers, imitation movements of winter sports-specific motions, etc.). However, in many cases, there is an evident need to bring the lab to the field and assess health and performance-related aspects within representative real-life settings (Spörri et al., 2016). On the other hand, youth athletes need special care because they are particularly susceptible to the long-term consequences of sports participation and injuries during phases of biological maturation and rapid musculoskeletal growth (Schoeb et al., 2020). However, there is great potential in young athletes being more familiar with digitalization and consequently better able to use new technologies.

Accordingly, the main objective of our Research Topic entitled "Health and Performance Assessment in Winter Sports" was to emphasize the relationship between health, performance, and technology, and to highlight current challenges in the design of innovative measuring systems, wearable sensors, and assessment protocols for examining and monitoring health and performance in sports like Freestyle, Alpine, Nordic and Paralympic skiing. It was also intended to compile research articles focusing on the application of digitalization and technology in the context of performance enhancement, injury prevention, and rehabilitation.

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Specialty section:
This article was submitted to Sports Science, Technology and Engineering, a section of the journal Frontiers in Sports and Active Living

Received: 12 November 2020
Accepted: 12 February 2021
Published: 09 March 2021

Citation:
Spörri J, Stöggl T and Aminian K (2021) Editorial: Health and Performance Assessment in Winter Sports. Front. Sports Act. Living 3:628574. doi: 10.3389/fspor.2021.628574

CURRENT TRENDS OF HEALTH AND PERFORMANCE ASSESSMENT IN WINTER SPORTS

Recent advances in digitization and measurement technology have also influenced youth and elite winter sports. Current trends of health and performance assessment can be summarized as: (1) new technologies and approaches for motion analysis with a clear tendency toward wearables, large capture volumes and long-term assessments (Supej, 2010; Gilgien et al., 2013, 2015; Fasel et al., 2017a,b; Spörri et al., 2017; Fasel et al., 2018; Gløersen et al., 2018a,b; Takeda et al., 2019; Neuwirth et al., 2020); (2) digital data collections, interdisciplinary/integrative measurement setups, advanced signal processing and state-of-the-art data analytics such as machine learning in connection with performance assessment and enhancement (Rindal et al., 2017; Jang et al., 2018; Losnegard et al., 2019; Ostrek et al., 2019; Skattebo et al., 2019; Heinrich et al., 2020; Solli et al., 2020); (3) mobile Health (mHealth) applications, supporting engineering solutions, and technology-based athlete screening in the context of injury/illness surveillance and prevention (Steenstrup et al., 2018; Schindelwig et al., 2019; Ellenberger et al., 2020a,b; Franchi et al., 2020; Fröhlich et al., 2020; Hermann and Senner, 2020); and (4) comprehensive monitoring/test protocols, and the objectification of clinical criteria in the return-to-sport context (Jordan et al., 2015a,b; Jordan et al., 2018; Csapo et al., 2019).

Fully in line with these current trends, our Research Topic on "Health and Performance Assessment in Winter Sports" compromises a total of 13 research articles, all of which can be assigned to one of the trend areas mentioned above (see **Table 1**). Of these articles, 11 were original research articles, one a perspective and one a methods article. Most articles were cross-sectional observations, while there were only three articles based on other study designs (one case study, one intervention study, and one literature review).

With respect to new technologies and approaches, Martinez, Brunauer et al. developed and validated a gyroscope-based ski turn detection algorithm for an on-snow application under various conditions. For many health and performance-related applications in alpine skiing, an exact determination of separate turn cycles is key (Spörri et al., 2012, 2018). An alternative, vertical ground-reaction force(GRF)-based approach was investigated in Martinez, Nakazato et al. In their study, they compared different functional definition criteria, as well as portable force platforms vs. pressure insoles for the determination of turn switches during alpine skiing. Supej et al. summarized the current state of scientific knowledge on methodological and practical aspects of the assessment of alpine skiing performance by Global Navigation Satellite Systems (GNSS) and stimulated future perspectives on the topic. GNSS-based performance assessments have been widely used in research on alpine and cross-country skiers (Supej, 2010; Gilgien et al., 2013, 2015; Gløersen et al., 2018a), and many skiing teams already employ GNSS technology in their daily training and equipment testing routines. Thus, in combination with advanced computer software, they are a good example of how the digital revolution has also taken hold in winter sports.

With regard to performance assessment and enhancement, the current Research Topic offers a broad spectrum of digitalization and technology-driven sample applications in the fields of alpine skiing, cross-country skiing, and biathlon. Alhammoud et al. and Bruhin et al. for example, have used state-of-the-art wearable measurement technologies to analyse the racecourse (e.g., course setting, steepness, etc.) and motion patterns/performance characteristics (e.g., joint angles, speed, time per turn, turn phases, etc.) of competitive alpine skiers at all levels and within different alpine disciplines. Moreover, Reid et al. used a complex video-based 3D kinematic analysis to quantify the ski motion characteristics during alpine slalom skiing and compare these measures with theoretical predictions based on ski geometry. Two interesting application examples of integrative measurement setups that use combined interdisciplinary research approaches (such as biomechanics and physiology), are the study on the influence of sitting posture on the sit-skiing economy by Lajunen et al. and the study on the determinants of biathlon competition performance by Luchsinger et al. Finally, Steidl-Müller et al. investigated whether the relative age effect in youth competitive alpine skiing changed over the last decade; a comprehensive analysis with the data of more than 1,400 athletes, which benefits from today's digitalization in competitive sports.

In the context of injury/illness surveillance and prevention, the study by Doyle-Baker and Emery presented some interesting new data on physical activity, injury, and illness among adolescent skiers. Despite all technological advances and booming mHealth applications, trustworthy information provided by athletes and self-reported data from various stakeholders of the sport remains an important pillar for load management and injury registration. This also applies to the study by Westin et al. who evaluated a sports-specific anterior cruciate ligament (ACL) injury prevention programme based on a systematic injury monitoring system, installed at Swedish ski high schools. In their study, they reported a promising 45% reduction in the incidence rate of ACL injuries among young competitive alpine skiers when a prevention program consisting of neuromuscular exercise was implemented. Additionally, the review by Hanstock et al. aimed to provide an overview of pathophysiological responses to exercise at sub-zero temperatures and identify the potential of heat-and-moisture-exchanging breathing devices to prevent airway pathophysiological responses to cold air exercise.

In terms of return-to-sport, this Research Topic is complemented by the case study of Jordan et al. which presented a detailed analytical framework for return-to-sport training and neuromuscular testing used in an elite female alpine ski racer following ACL reconstruction. Interestingly, the authors reported that functional and strength deficits persisted up to 18 months post-surgery; a fact that further supports the use of an athlete monitoring approach that tracks them throughout the return-to-sport/return-to-performance transitions, rather than a discrete timepoint clearance approach. In this context, technology has

TABLE 1 | Overview of the published research articles categorized by area, winter sports, article type/study design, and subjects.

Area	Winter sports	Article type/Study design	Subjects	References
New technologies and approaches				
Gyroscopes for turn switch detection	Alpine skiing	Original research article/cross-sectional study	$n = 11$	Martinez, Brunauer et al.
Pressure insoles vs. force plates for turn switch detection	Alpine skiing	Original research/cross-sectional study	$n = 20$	Martinez, Nakazato et al.
GNSS for performance analysis (skier kinematics)	Alpine skiing	Perspective article/literature review	n/a	Supej et al.
Performance assessment and enhancement				
Discipline-dependent knee and hip joint kinematics using electro-goniometers	Alpine skiing	Original research article/cross-sectional study	$n = 20$	Alhammoud et al.
Level-, course and terrain-dependent performance analysis by GNSS	Alpine skiing	Original research article/cross-sectional study	$n = 57$	Bruhin et al.
Effect of sitting posture on sit-skiing economy based on an interdisciplinary/integrative measurement set-up	Paralympic Cross-Country skiing	Original research article/cross sectional study	$n = 10$	Lajunen et al.
Determinants of competition performance based on an interdisciplinary/integrative measurement set-up	Biathlon	Original research article/cross-sectional study	$n = 11$	Luchsinger et al.
Skier technique and tactic analysis by video-based 3D kinematics	Alpine skiing	Original research article/cross-sectional study	$n = 6$	Reid et al.
Relative age effect in youth competitive alpine skiers based on a comprehensive database	Alpine skiing	Original research article/cross-sectional study	$n = 1,466$	Steidl-Müller et al.
Injury/illness surveillance and prevention				
Self-reported physical activity, injury, and by using an online questionnaire	Alpine skiing	Original research article/cross-sectional study	$n = 96$	Doyle-Baker and Emery
Exercise in the cold with special focus on heat-and-moisture-exchanging breathing devices	Cross-Country skiing	Original research article/cross-sectional study	n/a	Hanstock et al.
Evaluation of a sports-specific injury prevention program based systematic injury monitoring system	Alpine skiing	Original research article/intervention study with historical controls	$n = 736$	Westin et al.
Return-to-sport				
Monitoring the return-to-sport transition after ACL injury by digital self-reporting and neuromuscular testing	Alpine skiing	Methods article/case study	$n = 1$	Jordan et al.

GNSS, Global Navigation Satellite Systems; 3D, Three-dimensional; ACL, anterior cruciate ligament.

great potential for the development of standardized and reliable neuromuscular assessment protocols and objective criteria.

WHERE TO GO FROM HERE?

Given these general trends, new research articles, and the current state of scientific knowledge on health and performance assessment in winter sports, there are challenges that need to be addressed in the future.

New Technologies and Approaches in General

- To be attractive for sports practitioners, new technologies and engineering solutions should be easy to use/calibrate and not hinder athletes with cumbersome multiple sensors, fixations, and connections. Ideally, sensors and electronics should be integrated or simply fixed into the athletes' standard equipment.
- However, industry and end-users must care about the objectivity, validity, and reliability of the technology applied. For effective decision-making in coaching and clinical practice, imprecise or even incorrect information can be worse than no additional information.

Health and Performance Assessment

- New technologies and approaches should be used for providing evidence, not to confirm single observations and personal beliefs.
- A systematic and longitudinal collection of data is crucial. Here proceeding digitalization and technological development will help.
- Drawing practically relevant conclusions from a wealth of data *(information)* through data analytics *(knowledge)* will be one of our greatest challenges in the near future. In this context, the ongoing digitalization and new technological trends may provide significant support.

- An integrative fusion of different technologies and disciplines (e.g., biomechanics, physiology, psychology) will most likely become the new state-of-the-art in terms of health and performance assessment in winter sports.

AUTHOR CONTRIBUTIONS

JS, TS, and KA designed and edited this Research Topic. JS wrote the first draft of the corresponding editorial. All authors contributed to the manuscript and approved the final version.

REFERENCES

Csapo, R., Hoser, C., Gföller, P., Raschner, C., and Fink, C. (2019). Fitness, knee function and competition performance in professional alpine skiers after ACL injury. *J. Sci. Med. Sport* 22, S39–S43. doi: 10.1016/j.jsams.2018.06.014

Düking, P., Achtzehn, S., Holmberg, H.-C., and Sperlich, B. (2018). Integrated framework of load monitoring by a combination of smartphone applications, wearables and point-of-care testing provides feedback that allows individual responsive adjustments to activities of daily living. *Sensors* 18:1632. doi: 10.3390/s18051632

Ellenberger, L., Jermann, J., Fröhlich, S., Frey, W. O., Snedeker, J. G., and Spörri, J. (2020a). Biomechanical quantification of deadbug bridging performance in competitive alpine skiers: reliability, reference values, and associations with skiing performance and back overuse complaints. *Phys. Ther. Sport* 45, 56–62. doi: 10.1016/j.ptsp.2020.05.013

Ellenberger, L., Oberle, F., Lorenzetti, S., Frey, W. O., Snedeker, J. G., and Spörri, J. (2020b). Dynamic knee valgus in competitive alpine skiers: observation from youth to elite and influence of biological maturation. *Scand. J. Med. Sci. Sports* 30, 1212–1220. doi: 10.1111/sms.13657

Fasel, B., Gilgien, M., Spörri, J., and Aminian, K. (2018). A new training assessment method for alpine ski racing: estimating center of mass trajectory by fusing inertial sensors with periodically available position anchor points. *Front. Physiol.* 9:1203. doi: 10.3389/fphys.2018.01203

Fasel, B., Spörri, J., Schutz, P., Lorenzetti, S., and Aminian, K. (2017a). An Inertial Sensor-Based Method for Estimating the Athlete's Relative Joint Center Positions and Center of Mass Kinematics in Alpine Ski Racing. *Front. Physiol* 8:850. doi: 10.3389/fphys.2017.00850

Fasel, B., Spörri, J., Schutz, P., Lorenzetti, S., and Aminian, K. (2017b). Validation of functional calibration and strap-down joint drift correction for computing 3D joint angles of knee, hip, and trunk in alpine skiing. *PLoS ONE* 12:e0181446. doi: 10.1371/journal.pone.0181446

Franchi, M. V., Fitze, D. P., Hanimann, J., Sarto, F., and Spörri, J. (2020). Panoramic ultrasound vs. MRI for the assessment of hamstrings cross-sectional area and volume in a large athletic cohort. *Sci. Rep.* 10:14144. doi: 10.1038/s41598-020-71123-6

Fröhlich, S., Helbling, M., Fucentese, S. F., Karlen, W., Frey, W. O., and Spörri, J. (2020). Injury risks among elite competitive alpine skiers are underestimated if not registered prospectively, over the entire season and regardless of whether requiring medical attention. *Knee Surg. Sports Traumatol. Arthrosc.* doi: 10.1007/s00167-020-06110-5. [Epub ahead of print].

Gilgien, M., Spörri, J., Chardonnens, J., Kröll, J., Limpach, P., and Müller, E. (2015). Determination of the centre of mass kinematics in alpine skiing using differential global navigation satellite systems. *J. Sports Sci.* 33, 960–969. doi: 10.1080/02640414.2014.977934

Gilgien, M., Spörri, J., Chardonnens, J., Kröll, J., and Müller, E. (2013). Determination of external forces in alpine skiing using a differential global navigation satellite system. *Sensors* 13, 9821–9835. doi: 10.3390/s130809821

Gløersen, Ø., Kocbach, J., and Gilgien, M. (2018a). Tracking performance in endurance racing sports: evaluation of the accuracy offered by three commercial GNSS receivers aimed at the sports market. *Front. Physiol.* 9:1425. doi: 10.3389/fphys.2018.01425

Gløersen, Ø., Losnegard, T., Malthe-Sørenssen, A., Dysthe, D. K., and Gilgien, M. (2018b). Propulsive power in cross-country skiing: application and limitations of a novel wearable sensor-based method during roller skiing. *Front. Physiol.* 9:1631. doi: 10.3389/fphys.2018.01631

Heinrich, A., Hansen, D. W., Stoll, O., and Cañal-Bruland, R. (2020). The impact of physiological fatigue and gaze behavior on shooting performance in expert biathletes. *J. Sci. Med. Sport* 23, 883–890. doi: 10.1016/j.jsams.2020.02.010

Hermann, A., and Senner, V. (2020). Knee injury prevention in alpine skiing. A technological paradigm shift towards a mechatronic ski binding. *J. Sci. Med. Sport.* doi: 10.1016/j.jsams.2020.06.009. [Epub ahead of print].

Jang, J., Ankit, A., Kim, J., Jang, Y. J., Kim, H. Y., Kim, J. H., et al. (2018). A unified deep-learning model for classifying the cross-country skiing techniques using wearable gyroscope sensors. *Sensors* 18:3819. doi: 10.3390/s18113819

Jordan, M. J., Aagaard, P., and Herzog, W. (2015a). Lower limb asymmetry in mechanical muscle function: a comparison between ski racers with and without ACL reconstruction. *Scand. J. Med. Sci. Sports* 25, e301–e309. doi: 10.1111/sms.12314

Jordan, M. J., Aagaard, P., and Herzog, W. (2015b). Rapid hamstrings/quadriceps strength in ACL-reconstructed elite alpine ski racers. *Med. Sci. Sports Exerc.* 47, 109–119. doi: 10.1249/MSS.0000000000000375

Jordan, M. J., Aagaard, P., and Herzog, W. (2018). A comparison of lower limb stiffness and mechanical muscle function in ACL-reconstructed, elite, and adolescent alpine ski racers/ski cross athletes. *J. Sport Health Sci.* 7, 416–424. doi: 10.1016/j.jshs.2018.09.006

Khundaqji, H., Hing, W., Furness, J., and Climstein, M. (2020). Smart shirts for monitoring physiological parameters: scoping review. *JMIR MHealth UHealth* 8:e18092. doi: 10.2196/18092

Losnegard, T., Tosterud, O. K., Trøen, E., Carlsen, C. H., Paulsen, G., and Rud, B. (2019). The influence of pole lengths on O2-cost, kinematics, and performance in double poling at high speeds before and after a training period with long poles. *Eur. J. Appl. Physiol.* 119, 2579–2587. doi: 10.1007/s00421-019-04237-z

Lutz, J., Memmert, D., Raabe, D., Dornberger, R., and Donath, L. (2019). Wearables for integrative performance and tactic analyses: opportunities, challenges, and future directions. *Int. J. Environ. Res. Public Health* 17:59. doi: 10.3390/ijerph17010059

Neuwirth, C., Snyder, C., Kremser, W., Brunauer, R., Holzer, H., and Stöggl, T. (2020). Classification of alpine skiing styles using GNSS and inertial measurement units. *Sensors* 20:4232. doi: 10.3390/s20154232

Ostrek, M., Rhodin, H., Fua, P., Müller, E., and Spörri, J. (2019). Are existing monocular computer vision-based 3D Motion capture approaches ready for deployment? A methodological study on the example of alpine skiing. *Sensors* 19:4323. doi: 10.3390/s19194323

Rindal, O., Seeberg, T., Tjønnås, J., Haugnes, P., and Sandbakk, Ø. (2017). Automatic classification of sub-techniques in classical cross-country skiing using a machine learning algorithm on micro-sensor data. *Sensors* 18:75. doi: 10.3390/s18010075

Rommers, N., Rössler, R., Verhagen, E., Vandecasteele, F., Verstockt, S., Vaeyens, R., et al. (2020). A machine learning approach to assess injury risk in elite youth football players. *Med. Sci. Sports Exerc.* 52, 1745–1751. doi: 10.1249/MSS.0000000000002305

Schindelwig, K., Platzer, H.-P., Mössner, M., and Nachbauer, W. (2019). Safety recommendations of winter terrain park jumps into airbags. *J. Sci. Med. Sport* 22, S50–S54. doi: 10.1016/j.jsams.2018.09.229

Schoeb, T., Peterhans, L., Fröhlich, S., Frey, W. O., Gerber, C., and Spörri, J. (2020). Health problems in youth competitive alpine skiing: a 12-month observation of 155 athletes around the growth spurt. *Scand. J. Med. Sci. Sports* 29, 1254–1264. doi: 10.1111/sms.13740

Skattebo, Ø., Losnegard, T., and Stadheim, H. K. (2019). Double-poling physiology and kinematics of elite cross-country skiers: specialized long-distance versus all-round skiers. *Int. J. Sports Physiol. Perform* 14, 1190–1199. doi: 10.1123/ijspp.2018-0471

Solli, G. S., Sandbakk, S. B., Noordhof, D. A., Ihalainen, J. K., and Sandbakk, Ø. (2020). Changes in self-reported physical fitness, performance, and side effects across the phases of the menstrual cycle among competitive endurance athletes. *Int. J. Sports Physiol. Perform* 15, 1324–1333. doi: 10.1123/ijspp.2019-0616

Sperlich, B., Aminian, K., Düking, P., and Holmberg, H.-C. (2020). Editorial: wearable sensor technology for monitoring training load and health in the athletic population. *Front. Physiol.* 10:1520. doi: 10.3389/fphys.2019.01520

Spörri, J., Kröll, J., Fasel, B., Aminian, K., and Müller, E. (2017). the use of body worn sensors for detecting the vibrations acting on the lower back in alpine ski racing. *Front. Physiol* 8:522. doi: 10.3389/fphys.2017.00522

Spörri, J., Kröll, J., Schwameder, H., and Müller, E. (2018). The role of path length- and speed-related factors for the enhancement of section performance in alpine giant slalom. *Eur. J. Sport Sci.* 18, 911–919. doi: 10.1080/17461391.2018.1453870

Spörri, J., Kröll, J., Schwameder, H., Schiefermüller, C., and Müller, E. (2012). Course setting and selected biomechanical variables related to injury risk in alpine ski racing: an explorative case study. *Br. J. Sports Med.* 46, 1072–1077. doi: 10.1136/bjsports-2012-091425

Spörri, J., Schiefermüller, C., and Müller, E. (2016). Collecting kinematic data on a ski track with optoelectronic stereophotogrammetry: a methodological study assessing the feasibility of bringing the biomechanics lab to the field. *PLoS ONE* 11:e0161757. doi: 10.1371/journal.pone.0161757

Steenstrup, S. E., Mok, K. M., Mcintosh, A. S., Bahr, R., and Krosshaug, T. (2018). Head impact velocities in FIS world cup snowboarders and freestyle skiers: do real-life impacts exceed helmet testing standards? *Br. J. Sports Med.* 52, 32–40. doi: 10.1136/bjsports-2016-097086

Supej, M. (2010). 3D measurements of alpine skiing with an inertial sensor motion capture suit and GNSS RTK system. *J. Sports Sic.* 28, 759–769. doi: 10.1080/02640411003716934

Takeda, M., Miyamoto, N., Endo, T., Ohtonen, O., Lindinger, S., Linnamo, V., et al. (2019). Cross-Country skiing analysis and ski technique detection by high-precision kinematic global navigation satellite system. *Sensors* 19:4947. doi: 10.3390/s19224947

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.

frontiers in Sports and Active Living

ORIGINAL RESEARCH
published: 06 September 2019
doi: 10.3389/fspor.2019.00018

Development and Validation of a Gyroscope-Based Turn Detection Algorithm for Alpine Skiing in the Field

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Several methodologies have been proposed to determine turn switches in alpine skiing. A recent study using inertial measurement units (IMU) was able to accurately detect turn switch points in controlled lab conditions. However, this method has yet to be validated during actual skiing in the field. The aim of this study was to further develop and validate this methodology to accurately detect turns in the field, where factors such as slope conditions, velocity, turn length, and turn style can influence the recorded data. A secondary aim was to identify runs. Different turn styles were performed (carving long, short, drifted, and snowplow turns) and the performance of the turn detection algorithm was assessed using the ratio, precision, and recall. Short carved turns showed values of 0.996 and 0.996, carving long 1.007 and 0.993, drifted 0.833 and 1.000 and snowplow 0.538 and 0.839 for ratio and precision, respectively. The results indicated that the improved system was valid and accurate for detecting runs and carved turns. However, for drifted turns, while all the turns detected were real, some real turns were missing. Further development needs to be done to include snowplow skiing.

Keywords: carving, drifted turns, IMU, sensor, ski

OPEN ACCESS

Edited by:
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University of Sassari, Italy

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Specialty section:
This article was submitted to Sports Science, Technology and Engineering, a section of the journal Frontiers in Sports and Active Living

Received: *13 June 2019*
Accepted: *19 August 2019*
Published: *06 September 2019*

Citation:
Martínez A, Brunauer R, Venek V, Snyder C, Jahnel R, Buchecker M, Thorwartl C and Stöggl T (2019) Development and Validation of a Gyroscope-Based Turn Detection Algorithm for Alpine Skiing in the Field. Front. Sports Act. Living 1:18. doi: 10.3389/fspor.2019.00018

INTRODUCTION

Turn detection in alpine skiing has been a topic of growing interest over the last 15 years. Turns are the basic unit required for detailed analysis or interpretation of skiing data such as edge angle, symmetry, or turn phases (Müller and Schwameder, 2003; Spörri et al., 2012; Supej et al., 2013; Hébert-Losier et al., 2014). Thus, it is essential to determine when each turn begins (Spörri et al., 2012). Several sensor configurations and methodologies have been proposed to define turn switches. For example, the crossing point between the center of mass (CoM) and the ski trajectories (Supej et al., 2003), the minimum ground reaction force (Nakazato et al., 2011), the instant when the vertical distance of the right ankle joint and left ankle joint to CoM vectors are equal (Fasel et al., 2016b) and the deflection point of the CoM trajectory (Gilgien et al., 2018). Although those methodologies are useful for turn detection, they present some disadvantages that make them not feasible for use on a regular basis. These methods require time consuming preparation, labor-intensive post processing, or alterations in the athlete comfort that make them disadvantageous for regular in-field use.

Inertial measurement unit (IMU) sensor technology has been proposed as a promising alternative approach (Gouwanda and Senanayake, 2008; Fasel et al., 2016b; Yu et al., 2016; Martínez et al., 2019). Smartphones are already used to collect, receive, store, and analyze data collected by wireless sensors, which have progressively become smaller and longer lasting (Kranz et al., 2013; Bondaronek et al., 2018). Based on this development, inquiries are no longer limited to single or double turns, a limitation of some methodologies (Supej et al., 2003; Spörri et al., 2012). Currently, it is possible to perform data collection over longer runs, implementing IMU technologies into the skier's equipment.

Recently, there have been some studies proposing turn detection systems based on simple IMU configurations. Those methodologies are unobtrusive for the athlete avoiding possible alterations in the data related to comfort or technique modification. Yu et al. (2016) placed several IMUs on a single elite skier during part of routine on-slope training for giant slalom and 48 turns were assessed. They computed the angle of each IMU roll axis relative to the vertical to count turns and concluded that the best placements for the IMUs were the pelvis, shank, and foot. Although the system was able to count turns properly, they did not report the turn switch points. A second method was developed with the goal of counting and differentiating right and left turns. Jones et al. (2016) proposed a machine learning approach. They placed a customized sensor consisting on an accelerometer and a gyroscope below the skier's knee. After training the system, ∼87% of the turns were detected. Similar to the previous method, this approach aimed only to count turns, not define turn switch point. Both methods were only developed and tested on single skiers. Another methodology was proposed by our research group (Martínez et al., 2019) and was based on two IMUs, placed on the upper cuff of each ski boot. The study was performed in a laboratory environment using a ski-ergometer. The algorithm developed was based on the gyroscope signal and detected turn switch points with a precision of ± 0.03 s. It was hypothesized that this methodology would work for all parallel skiing styles (i.e., carving and drifted turns in all radii), while previous methodologies had focused mostly on slalom or giant slalom race conditions (Supej et al., 2003; Ulrich et al., 2015; Yu et al., 2016). However, this method has not been validated during actual skiing in the field [with the exception of the reported one participant pilot (Martínez et al., 2019)].

Methods such as the aforementioned, allow for extended data collection. As the amount of data collected grows, it seems appropriate to differentiate not only between turns but also between runs since skiing usually consists on multiple sequences of turns. This would allow for a better organization and classification of the data, and potentially for real time analysis. To our knowledge, there is a lack of methodologies to automatically segment ski runs based on non-obtrusive methodology.

The validation of the algorithm used in this study was based on the accurate detection of each turn. Hence, the goals of this study were 2-fold, (1) to further develop and validate the algorithm of Martínez et al. (2019) in field conditions including different turn styles and lengths, and (2) to automatically detect and segment turn sequences.

MATERIALS AND METHODS

For the validation and development of the turn detection algorithm, an experiment was designed where an IMU was attached to each ski boot (Martínez et al., 2019) and a camera placed on the chest to serve as a reference. The turn styles assessed were: carving long, carving short, drifted turns and snowplow steering. Participants were instructed to perform long turns over an 8 m corridor, approximately defined by the width of two snow groomer tracks, and short turns within a 4 m corridor, approximately defined by one groomer width. This provided a consistent reference for turn size, without explicitly controlling or defining turn size or shape. Each participant performed a turn sequence including at least 10 turns for each skiing style. The test slope was a red slope (#1) at Mölltaler Glacier in Flattach, Austria, which is steeper in the upper half and moderate in the lower half. Two skiing styles were performed within each run. The first run included carving short on the upper half and carving long on the lower half; while the second run consisted on drifted turns on the upper half and snowplow steering on the lower half. The algorithm development process consisted of several evaluation—development iterations where weaknesses were evaluated, adjusted, and tested again.

Participants

Eleven male expert skiers (Mean ± SD: Age 26.2 ± 5.9 year; Height = 179.4 ± 5.9 cm; Mass = 77.0 ± 5.4 kg) volunteered for the study. All participants were expert skiers, with experience as ski racers or ski instructors. Before the measurements were conducted, they were informed in detail about the testing procedure, as well as possible benefits and risks of the investigation prior to signing the consent form approved by the local Ethics Committee (EK-GZ: 11/2018). The experiment was conducted in accordance with the Declaration of Helsinki.

Instruments

An IMU (LSM6DS3, 2.5 × 3 × 0.83 mm, ± 8 g and ± 500 dps full scale, STMicroelectonics, Amsterdam, Netherlands) was placed in the back of the upper cuff of each boot (Hawx 130, Atomic, Altenmarkt, Austria). The X axis of the IMU was aligned with the vertical axis of the boot (yaw) pointing superiorly, the Y with the lateral axis (pitch) pointing to the left, and the Z with the anterior-posterior axis (roll) pointing posteriorly (**Figure 1**). The IMU was fixed using a tight elastic strap and a customized rigid housing to avoid movement or misalignments. Angular velocities from the gyroscope signals were collected at 833 Hz, analog and digital low-pass filters were applied directly by the IMU after A/D conversion, and the signal was forwarded via Bluetooth at 64 Hz. The sensor data was collected and stored by an in-house smartphone application (SkiSense App, Salzburg Research, Salzburg, Austria).

In order to define reference turn switch points and determine the proper detection of turns (e.g., real turns not detected or turns erroneously detected), all runs were recorded with a camera (Hero4 Session, GoPro, San Mateo, CA, USA) with

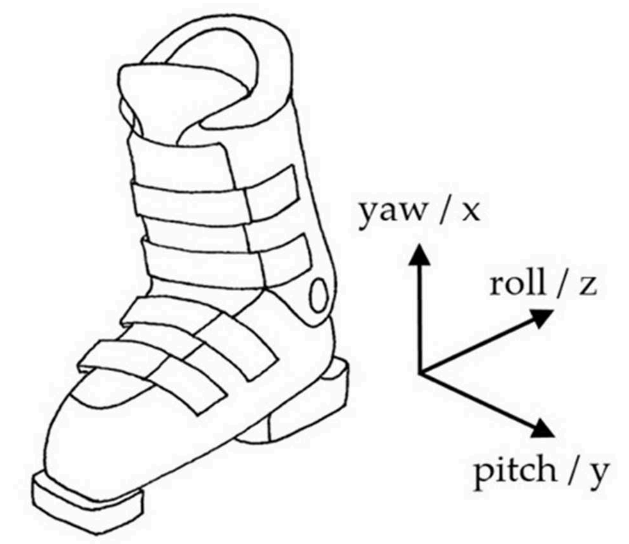

FIGURE 1 | Definition of axes. The positive roll axis is parallel to the ski's surface pointing posteriorly.

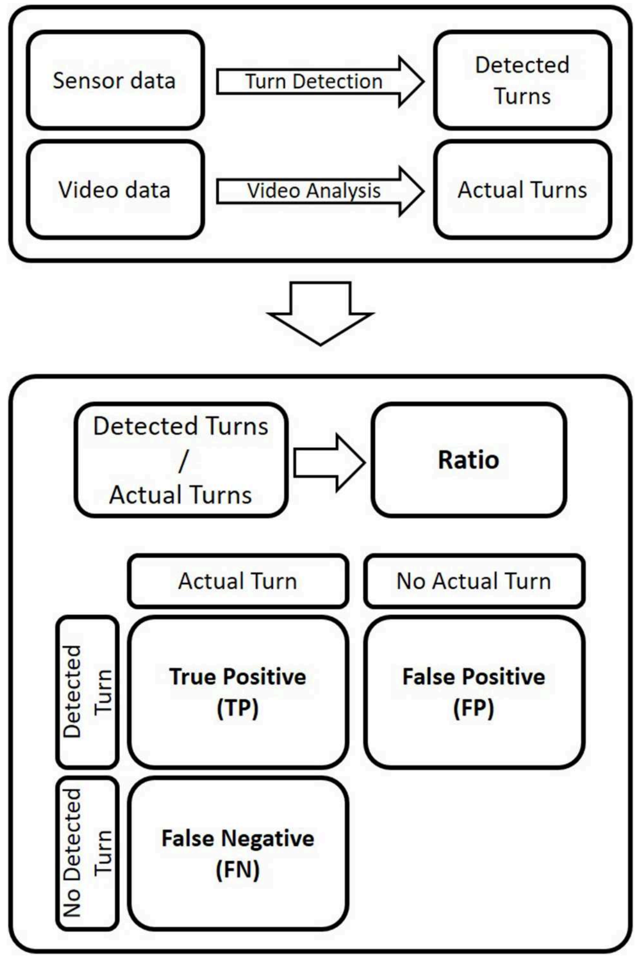

FIGURE 2 | Data flow from field measurements to data used for the validation and performance metrics. Determination of the ratio between the number of turns detected and actual turns and computation of the metrics used to calculate precision and recall.

a sampling rate of 25 Hz. The camera was placed on the skiers' chests using an adjustable chest harness, and positioned such that the field of view included both skis, boots and the surrounding area.

Data Preparation

Video data was analyzed by experienced raters, labeling relevant events or context, such as turn switch point, turn direction, or jump. Turn switch points in the video analysis were defined as the frames where the surfaces of the skis were flat on the ground. Video and sensor data were synchronized using a jump event at the beginning and end of each trial. The jumps were detected in the vertical axis of the accelerometer and synchronized with the frame at landing. For validation, the actual turns obtained by the video analysis and the number of detected turns were used. The detected turns were computed by applying the turn detection algorithm (Martínez et al., 2019) to the sensor data (see **Figure 2**).

Evaluation Design

In order to validate the turn detection algorithm, three performance metrics were implemented: (1) ratio, (2) turn count precision, and (3) recall (see below). All steps of evaluation (i.e., data acquisition, video analysis, signal evaluation) were conducted in a blinded procedure.

- *Ratio:* the quotient between the number of turns detected by the algorithm and the number of turns labeled in the video data (see **Figure 2**). If the ratio is >1, the turn detection algorithm overestimates the number of actual turns, and vice versa. A ratio of one means that the number of detected turns and actual turns are the same, indicating a good performance of the turn detection. However, it does not indicate if all the detected turns were real turns, since only the number of turns is evaluated.
- *Turn count precision (P):* the proportion of turns detected by the algorithm that are actual turns (see Equation 1).
- *Recall (R):* the proportion of actual turns detected by the turn detection algorithm (see Equation 2).

In all metrics a value of 1 means a perfect performance.

To calculate the turn count precision and recall values, the following metric were determined (**Figure 2**):

- True positives are determined by a detected turn that was an actual turn (based on video). A correct detection is characterized by the correct turn direction (either left or right turn) and by the difference in time between the detected and the actual timestamp. If the time difference is smaller than half the mean duration of actual turns (for a run), it is a true positive.
- False positives reflect the number of detected turns that are not actual turns.

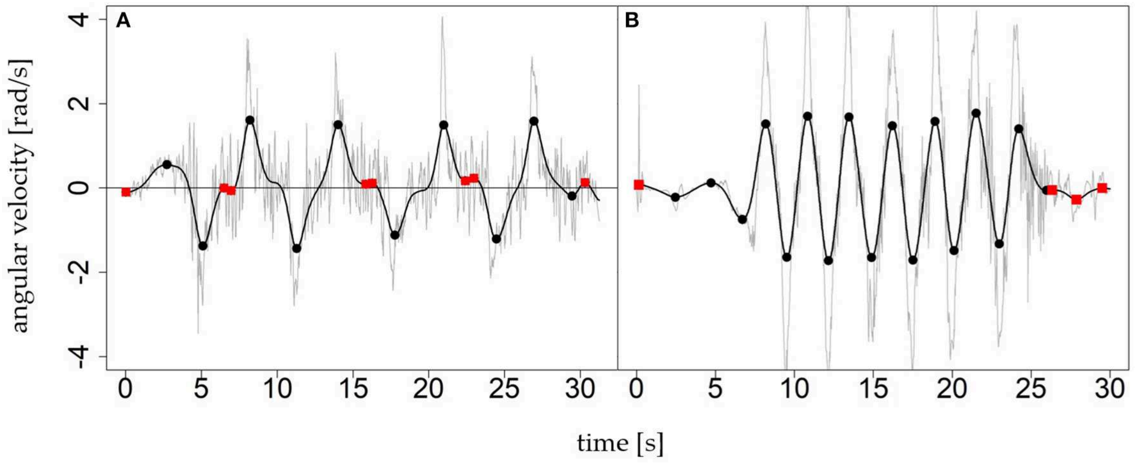

FIGURE 3 | Two examples of the roll signal ω_{roll} (gray) and decision signal ω_{ds} (black) of ski runs with several carving turns **(A)** and short turns **(B)**. The markers show local extrema; the black circles represent turn switches and the red squares are artifacts to be recognized and discarded.

- False negatives are the number of actual turns that are not detected by the turn detection algorithm.

$$P = TP \bullet (TP + FP)^{-1} \quad (1)$$

$$R = TP \bullet (TP + FN)^{-1} \quad (2)$$

Where P is the turn count precision, TP the true positives, FP the false positives, R the recall and FN the false negatives.

Algorithm Development

The purpose of the following algorithm was to determinate turn switches and sequences of parallel skiing turns. To keep the algorithm simple, it was assumed that a turn switch is a single point in time where both skis change from the uphill to downhill set of edges simultaneously. The performance metrics and video recordings were used to evaluate the performance of the current algorithm iteration (see section Evaluation design) and detect weaknesses.

The starting point was the evaluation of the algorithm developed under laboratory conditions by Martínez et al. (2019). Matlab (R2017B, MathWorks, Natick, MA, USA) and R (3.5.1, R Core Team, Auckland, New Zealand) were used to test and develop the algorithm. The roll axis (z) of the gyroscope signal from the left leg ω^l_{roll} and right leg ω^r_{roll} [rad/s] were used as input signal to calculate the turn switch points (**Figure 1**). High rotation rates (angular velocity) in the roll axis can have different causes (e.g., turning or skating). To restrict high rates to parallel turns, the arithmetic mean of both sides ω_{roll} smooths unilateral rotations. In the next step, a fourth-order zero-lag 0.5 Hz low-pass Butterworth (BW) (Martínez et al., 2019) was applied to produce a decision signal (ω_{ds}) that describes the rotation rate in the roll axis (**Figure 3**).

Figure 3 shows the local extrema in the two exemplary decision signals $\omega_{ds} = BW_{0.5}(-\omega_{roll})$. The left graph shows a sequence of nine carving turns (mean ± SD; turn duration of 2.97 ± 0.43 s), the right graph a sequence of 16 short turns (turn duration 1.04 ± 0.41 s). The minus before ω_{roll} flips the positive direction to anterior in agreement with the movement direction. The extrema indicate possible turn switches, whereby the sign of a value in ω_{ds} determines the turn direction. As **Figure 3** shows, local extrema are not necessarily caused by turn switches (red dots). There are other causes, especially when the signal oscillates with small amplitudes around zero after the skier has stopped. Furthermore, the constant cut-off frequency of 0.5 Hz is a trade off between damping the rotation rate of short turns too much and fostering artifacts (red dots/local extrema within turns) in long turns. Thus, as a next step, the algorithm goes through the sequence of all local extrema and labels each local extrema (**Figure 4**):

- *Switch:* This kind of local extrema indicates actual turn switches from left to right or right to left.
- *Noise:* Local extrema that happen within a turn are called noise. If a skier performs turns with longer duration (e.g., slowly skidded parallel turns or carving turns with a long stable edge angle), the decision signal ω_{ds} shows some artifacts as saddle points or small counter oscillations (**Figure 4**, green dots). These artifacts result in local extrema which are "within a turn" and do not indicate an actual turn switch.
- *Eliminated:* All other local extrema must be eliminated from the algorithm. These extrema are "outside a turn" and caused by small oscillations when the skier is not turning. For example, waiting, walking, or skiing straight downhill. The eliminated extrema are used to define the beginning and end of turn sequences.

Several heuristic rules were used for the labeling process:

1) *Switch*: Look at each pair of two consecutive local extrema: If two consecutive local maxima have a high rotation rate in $abs(\omega_{ds})$, opposite sign and a time distance >0.3 s and smaller than 5.0 s then label both as *switch*.
2) *Noise*: Look at each sequence of four consecutive local extrema: If both outer extrema fulfill rule 1 and both inner

local extrema not and if the rotation rates in $abs(\omega_{ds})$ of the inner are smaller than the outer then label both inner as *noise*.

3) *Eliminated*:

   (a) Look at each local extrema: If it is not labeled as *switch* or *noise* and if the rotation rate is smaller than a threshold then label as *eliminated*.
   (b) Look at each local extrema: If it is not labeled as *switch*, *noise* or *eliminated* and if it has the same sign in ω_{ds} as its predecessor then label as *eliminated*.
   (c) Look at each local extrema: If it is not labeled as *switch*, *noise*, or *eliminated* apply a decision tree (see below) to label it as *eliminated* or not.
   (d) Look at each local extrema: If it is not labeled as *switch*, *noise* or *eliminated* and if the predecessor and successor are *eliminated* then label as *eliminated*.

4) Remaining: Look at each local extrema: If it is not labeled as *switch*, *noise*, or *eliminated* then label as *switch*.

Decision tree (3c): the goal of the machine learning task was to obtain a simple rule that removes all remaining local extrema outside a turn sequence because these local extrema should have the label *eliminated*. If we do not have such a rule, rule 4 cannot be applied. A decision tree was trained by means of machine learning. The intent of the decision tree was to discriminate for each local extrema between the classes *within a turn sequence* or *not-eliminated* and *outside a turn sequence* or *eliminated*. Data were labeled by manually defining the time ranges of the turn sequences, and a cross-validation was used to avoid overfitting the decision tree. Obvious features as ω^r_{roll}, ω^l_{roll}, ω_{roll}, ω_{ds}, ω_{ds} (change in angular velocity between two consecutive local extrema), its absolute values $abs\,(\omega_{ds})$ and t were used to search the most expressive features. The result was the decision tree: $abs\,(\omega_{ds}) \le \theta_1 \wedge t \le \theta_2 \;\rightarrow$ *eliminated*. That means that the absolute value ω_{ds} and the t (time between two consecutive local extrema) were identified by the machine learning task as most expressive. The variables θ_1 and θ_2 are the modeling parameters of the machine learning model thresholds.

The result of the previous step is a turn sequence (TS) of labeled local extrema $TS_{ds,n}((t_n, \omega_{ds}(t_n), l_n))_{n\in\mathbb{N}}$. Next, the algorithm derives the turns $(t_{start}, t_{end}, d, s)$ from the sequence $TS_{ds,n}$. The timestamps t_{start} and t_{end} are the start and the end of a turn (turn switch points), the value $d \in \{left, right\}$ indicates turn direction and $s \in \mathbb{N}$ is the number of the turn sequence to which the turn belongs (**Figure 5**). The value of d depends on the orientation of positive roll axis. **Figure 1** shows a right-handed coordinate system with positive roll axis in the posterior direction. Thus, local maxima (positive rotation) indicate turn switches from left to right and local minima (negative rotation) from right to left. A continuous alternating sequence of turns is given, if $t_{end,i-1} = t_{start,i}$ respectively if the end of turn $i-1$ is the start of turn i, then $s_i = s_{i-1}$. If $t_{end,i-1} \neq t_{start,i}$, then turn i starts a new turn sequence and $s_i = s_{i-1} + 1$ (**Figure 5**). The start value of s_1 is 1. To determine the sequence of turns $T_{ds,m}((t_{start,m}, t_{end,m}, d_m, s_m))_{m\in\mathbb{N}}$ $(m < n)$, the algorithm iterates through the sequence and merges consecutive extrema with label switch to a turn if and only if they are no interruptions from local

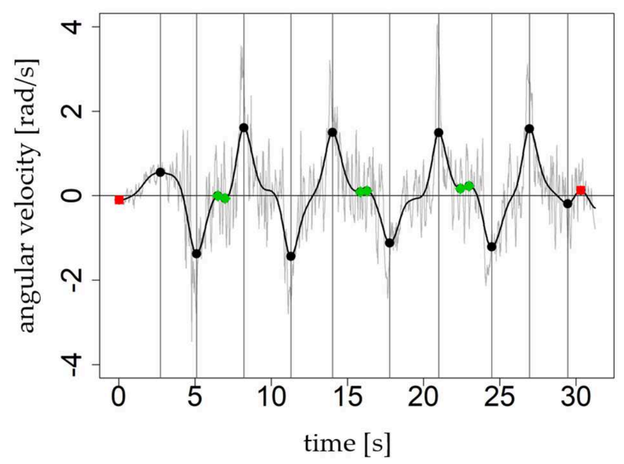

FIGURE 4 | The graph shows the proposed three types of labels for local extrema. Local extrema which are labeled as *switch* are black circles and additionally highlighted by the gray vertical line. The red squares represent local extrema with label *eliminated* and the green rhomboids outlines those with label *noise*. The average turn duration in this example is 2.97s and is longer than in **Figure 3**.

extrema with label eliminated. This rule produces a continuous turn sequence with $t_{end,i-1} = t_{start,i}$. Local extrema with label noise (per definition "within turn") were ignored because they do not interrupt a turn. Eliminated local extrema (per definition "outside turn") indicate an interruption of a consecutive turn sequence and causes $t_{end,i-1} \neq t_{start,i}$ and $s_i = s_{i-1} + 1$. The previous heuristic rules ensure that in a turn sequence each switch is followed by a switch with opposite sign, even in case were local extrema with label noise are between. A strict alternation of the sign is necessary because otherwise there is no alternation of left and right turns, which is not obvious.

The decision signal is a strongly smoothed signal. The rotation rates represent the general rotation behavior of (parallel) turning during skiing. The degree of smoothing between raw and decision signal can be observed in **Figures 4**, **6A**. To determine the turn switches more accurately, a higher cut-off frequency seems to be more advisable. As shown in the study of Martínez et al. (2019), $f_c = 3.0$ Hz is a proper cut-off frequency to perform such a "fine tuning." Therefore, a new fine tuning signal is defined by $\omega_{ft} = BW_{3.0}(-\omega_{roll})$ (**Figure 6A**). Then the algorithm searches for each $\left(t_i, \omega_{ds}(t_i), l_i\right)$ the global maximum or minimum in ω_{ft} in a time window (an asymmetric ε neighborhood) around the turn switch timestamp t_i. The algorithm "fine tunes" only local extrema labeled as switch and defines the global maximum or minimum $\omega_{ft}(t_i^{'})$ at $t_i^{'}$ as the new "fine tuned" turn switch. A percentage value or factor $p \in [0,1]$ defines the size of the asymmetric ε neighborhood (**Figure 6B**): $[t_i - p\,(t_i - t_{i-1})\,,\; t_i + p(t_{i+1} - t_i)]$.

For the succeeding evaluation we use 60% for the ε neighborhood, thus $p = 0.6$. Finally, the fine tuned turn switches, turns and turn sequences are based on the sequence $TS_{ft,n}((t_n^{'}, \omega_{ft}(t_n^{'}), l_n))_{n\in\mathbb{N}}$. Finally, the new sequence of fine tuned

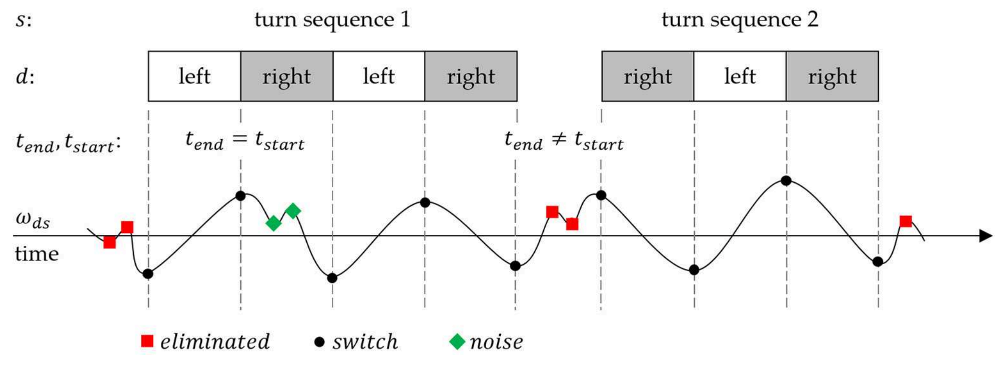

FIGURE 5 | The lower part shows an exemplary decision signal ω_{ds} with local extrema of type switch, noise and eliminated. The corresponding derived turns and turn sequences are shown above.

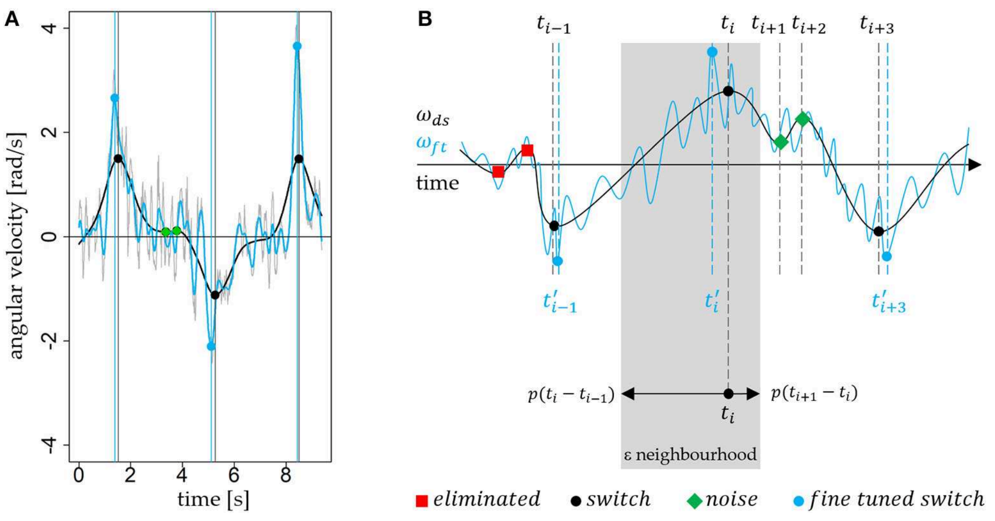

FIGURE 6 | (A) Comparison of the raw signal $-\omega_{roll}$ (gray), the filtered decision signal ω_{ds} (black, 0.5 Hz) and fine tuning signal ω_{ft} (blue, 3.0 Hz). The vertical blue and black lines show the effect of fine tuning, and the small shift in time. **(B)** The graph outlines (in gray) the definition of ε neighborhood graphically. A p of 0.6 defines a ε neighborhood (gray) where 60% of the distance to predecessor and successor extremum are part.

turns $T_{ft,m}((t'_{start,m}, t'_{end,m}, d_m, s_m))_{m\in\mathbb{N}}$ is given by substituting all t in $T_{ds,m}$ with t'.

RESULTS

The results of the turn detection evaluation for each skiing style (short and long carved, drifted, and snowplow turns) are shown in **Table 1**. The ratio between the detected and the actual carved turns (long and short turns pooled together) was 0.997, the best value of the different skiing styles analyzed (drifted 0.833, snowplow 0.538). A ratio of 0.997 indicates that the number of actual carving turns was slightly underestimated by the turn detection algorithm.

Investigating the turn precision measures of the algorithm for carved turns, almost all detected turns were correctly detected (turn precision was higher than 0.993 for both turn sequences). The recall measures were also high with values >0.990, which indicates that almost all actual turns were detected by the algorithm.

DISCUSSION

The purpose of this study was to develop and validate a turn detection algorithm for parallel alpine skiing turns in the field. The assumption that a turn switch is a single point in time where the edge changes simultaneously for both skis is not too critical if the turns have seamless transitions, and the skier performs parallel styles. Conversely, the algorithm is not able to count all turn styles accurately. For example, snowplow and drifted turns with low dynamics or straight piste crossings cause problems. However, the proposed methodology was aimed at continuous turn sequences of parallel style turns, as carved turns are usually the main subject of interest.

For validation, tests were performed by several subjects with diverse techniques, turn lengths, and snow conditions.

TABLE 1 | Evaluation metrics for each skiing style and group of styles in number of turns; ratio, turn count precision, and recall of each adapted confusion matrix.

Turn Sequence	AT	TP	FP	FN	Ratio	Precision	Recall
Short carved turns	231	230	1	2	0.996	0.996	0.991
Long carved turns	143	143	1	0	1.007	0.993	1
Drifted turns	132	109	0	22	0.833	1	0.833
Snowplow	104	47	9	57	0.538	0.839	0.452
TURN SEQUENCE GROUPED							
Carved	374	373	2	2	0.997	0.995	0.995
Parallel	506	482	2	24	0.953	0.996	0.953
All	610	529	11	81	0.867	0.980	0.867

AT, actual turns; TP, true positives; FP, false positives; FN, false negatives; Precision, turn count precision. Carved includes short and long carved turns. Parallel includes carved and drifted turns. All includes parallel and snowplow.

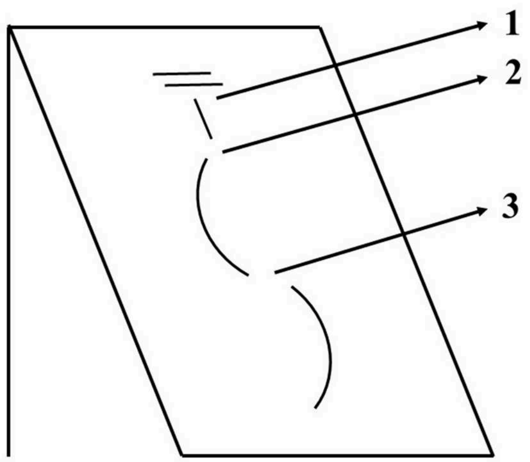

FIGURE 7 | Schematic representation of the beginning of a turn sequence and three different options for the first detected turn. Option 2 was the desired outcome.

The instructions for the different turn lengths aimed to define different types of turns (e.g., short and long) while allowing the participants to perform slightly different turns. We believe that not having an exact turn length adds an extra variability that is beneficial to develop a more robust algorithm. The natural variation in snow conditions across the 4 days of testing provided an additional layer of variability, adding to the robustness of the algorithm. The results of 374 carved turns (0.997 ratio, 0.995 precision, and 0.995 recall) prove the validity and robustness of this turn detection algorithm for this particular turning technique. Misdetections during carved turns were only observed at the beginning of the turn sequences; however, they were mostly counted correctly. The three different options observed for the initial turn detected in a turn sequence are shown in **Figure 7**. From 32 parallel turn sequences analyzed in this study, five were not properly detected. The system aimed to detect the first edge change out of the fall line (option 2 in **Figure 7**) and this first turn switch of each run was ignored and not included. Out of the five turn sequences not properly detected, two counted an extra turn (FP, option 1 in **Figure 7**) and three failed to count one turn (FN option 3 in **Figure 7**). Besides this issue with the beginning of the turn sequences, for carved turns, there were no other misdetections, all the turns within sequences were properly detected.

Ratio and recall for drifted turns (0.833 both values) were lower than for carved turns. The turn detection algorithm worked properly for all participants but four. For those participants, the missing turns were not isolated but consecutive (e.g., 2, 4, 6, and 9 consecutive turns). All those turns had some common characteristics. They were longer slow turns, which produced a less dynamic movement, and consequently were more affected by the snow conditions, in those cases, bumpy surfaces. The algorithm is prepared to recognize and cancel some noise (see **Figure 5**); however, when there is too much noise (e.g., more than two extra local maxima are detected between turns) the turn sequence is finalized. If there are several turns under those conditions, it does not report multiple sequences with single turns, but rather discards most of the turns since the first turn of every sequence is discarded. The possible misdetection of the first turn and the long low dynamic turns were the causes of some misdetection of turn sequences. When turn detection worked accurately, the sequences were properly defined and cut. Discriminating the signal depending on how dynamic the movement is could help to further develop the algorithm and overcome those missing turns.

Although the algorithm was developed for parallel turns, the performance during snowplow steering was also evaluated. While the turn count precision was acceptable, ratio and recall were unacceptably low (0.839, 0.538, and 0.452, respectively). As expected, most of the detected turns were actual turns, but many real turns were not detected. The snowplow turning style is completely different than drifted or carved turns. The legs do not have synchronized rotation rates in roll axis. The main movement does not rotate around the anterior-posterior axis, but around the vertical axis. Consequently, an algorithm that only takes into consideration the anterior-posterior axis might not be the most effective approach. However, snowplow turns are usually turns during learning and they are not used very often in everyday skiing. Thus, the focus on parallel turns is obvious, at least from a practical perspective. Further development, probably including a combination of more than one axis or a turn style detection system, would be needed for the automatic detection of snowplow turns.

Over the different iterations of the development process, modifications were included in the algorithm. These modifications were needed in order to cope with signal features that differed between in-lab (Martínez et al., 2019) and real skiing conditions. Due to the variable snow conditions, styles, turn lengths, and skiers, the signals recorded during skiing had more variability and some recurrent differences when compared to simulated turns on a ski glider. To confront this issue, some recurrent misdetections that did not corresponded with turn switch points (e.g., noise within turns or artifacts after stopping) were corrected, adding new rules to the algorithm and thus making it less simple. One of the additions was the decision tree. This decision tree is easy to implement by a single if condition. Thus, we preferred to use just a simple machine learning model, which is still human interpretable and implementable, to provide an additional heuristic rule. Such a simpler problem statement needs fewer data. However, it would be possible to generate a decision tree that is able to replace all the rules from 1 to 4. Such a decision tree would need more labeled data and the input for learning data would have to be more complex. It would be necessary to analyze at least a short sequence of local extrema. In our case, we looked only on the local extremum and its predecessor. This could be an approach for further optimization and automatization. However, for our proposed algorithm, machine learning was applied to provide final heuristic rule for the remaining local extrema. Furthermore, we limited the use of machine learning approaches in order to keep computational cost low, as this algorithm could be implemented in a smartphone app.

During the development process, some algorithm rules, and parameters were manually optimized to fine tune the algorithm. However, the algorithm presented in this publication is fully automatic, and does not require manual input. The results could however be influenced by IMU specifications such as sensitivity, sampling rate, and orientation.

For the validation of the turn detection algorithm, events such as falls were excluded from the study. One of the subjects fell during one trial, and two turns were detected based on this fall. Thus, in case of a fall, the algorithm might detect some extra turns.

The present methodology presents some advantages when compared to previously proposed methods. Yu et al. (2016) successfully counted turns using a single IMU. However, they only assessed one participant during a single giant slalom race trial, and the method was based on the angle with respect to the vertical. To properly calculate the orientation of the sensor, integration and drift correction computation procedures are needed (Seel et al., 2014; Fasel et al., 2018). This type of computation usually requires post-processing the data and makes it more difficult to perform analysis in real time and potentially limits the applications of this method. It is also important to consider that their goal was to count turns, therefore they did not report the turn switch points. The limitations of using video recording during skiing are well-known. There is limited capture volume (Supej et al., 2003; Fasel et al., 2016a), and it requires time consuming preparation and post processing (Reid, 2010). Furthermore, recent work from our research group showed that even in ideal lab conditions, the determination of the turn switch point using video recordings as a reference is challenging. Different raters, even with the same instructions, select different frames as the turn switch point (the reported range between raters was 51.4 ms; Martínez et al., 2019). For this reason, precision in the field was not measured in this study, but we can reasonably assume similar precision to that observed in the lab ($\pm$ 0.03 s). Since the nature of the movement on the ski-ergometer and during real skiing both follow our model of pendular movement, the basic features identified as turn switch points within the signals should be similar on the ski-ergometer and in the field. As such, the turn switch point determined by video analysis was only used as a reference to determine if the measured turn switch point corresponded to an actual turn switch.

CONCLUSION

In conclusion, the developed turn detection system is a valid, robust, and generally simple tool to detect parallel turns (carved and drifted) in alpine skiing with an accuracy of 95.3%. For carving turns, the algorithm is able to accurately detect 99.7% of actual carving turns. The algorithm is based only on a single axis of gyroscope data. Simple IMUs, securely mounted on both ski boots, provide sufficient data for the segmentation of time series signals into both turn sequences and single turns. Both are very convenient data structures for further analysis tasks. The approach is applicable for in-field studies because the devices do not disturb skiing and the algorithm is fully automated. Further research is needed to assess the performance of the system for skiers with different skill levels, or to include the detection of other turn styles, such as snowplow turns.

DATA AVAILABILITY

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the University of Salzburg. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

TS, RJ, and RB: conceptualization and investigation. TS, RJ, RB, MB, and AM: methodology. RB and MB: software. AM, VV, CT, and CS: validation. RB, MB, VV, and AM: formal analysis. TS and RB: resources. RJ, RB, and VV: data curation. AM, RB, and VV: writing-original draft preparation and visualization. CS, RJ, MB, TS, VV, and RB: writing-review and editing. TS: supervision, project administration, and funding acquisition.

FUNDING

No funding was received for this work from the National Institutes of Health, the Welcome Trust, the Howard Hughes Medical Institute, or other funding agencies to PubMed Central. Funding was provided based on the two Salzburg Trans-4-Tech projects Ski Sense and Sport Sense and by the Austrian Ministry for Transport, Innovation and Technology, the Federal Ministry for Digital and Economic Affairs, and the federal state of Salzburg under the research program COMET—Competence Centers for Excellent Technologies—in the project Digital Motion in Sports, Fitness and Well-being (DiMo).

ACKNOWLEDGMENTS

The authors would like to thank Elisabeth Häusler for her support during the project.

REFERENCES

Bondaronek, P., Alkhaldi, G., Slee, A., Hamilton, F. L., and Murray, E. (2018). Quality of publicly available physical activity apps: review and content analysis. *JMIR MHealth UHealth* 6:e53. doi: 10.2196/mhealth.9069

Fasel, B., Spörri, J., Chardonnens, J., Kröll, J., Müller, E., and Aminian, K. (2018). Joint inertial sensor orientation drift reduction for highly dynamic movements. *IEEE J. Biomed. Health Inform*. 22, 77–86. doi: 10.1109/JBHI.2017.2659758

Fasel, B., Spörri, J., Gilgien, M., Boffi, G., Chardonnens, J., Müller, E., et al. (2016a). Three-dimensional body and centre of mass kinematics in alpine ski racing using differential GNSS and inertial sensors. *Remote Sens*. 8:671. doi: 10.3390/rs8080671

Fasel, B., Spörri, J., Gilgien, M., Gerber, N., Falbriard, M., Müller, E., et al. (2016b). "IMU and GNSS-based turn switch detection in alpine ski racing," in *Abstract Book of the 7th International Congress on Science and Skiing* (St. Christoph am Arlberg).

Gilgien, M., Kröll, J., Spörri, J., Crivelli, P., and Müller, E. (2018). Application of dGNSS in alpine ski racing: basis for evaluating physical demands and safety. *Front. Physiol.* 9:145. doi: 10.3389/fphys.2018.00145

Gouwanda, D., and Senanayake, S. M. N. A. (2008). "Emerging trends of body-mounted sensors in sports and human gait analysis," in *4th Kuala Lumpur International Conference on Biomedical Engineering 2008* (Berlin; Heidelberg: Springer).

Hébert-Losier, K., Supej, M., and Holmberg, H. C. (2014). Biomechanical factors influencing the performance of elite Alpine ski racers. *Sports Med.* 44, 519–533. doi: 10.1007/s40279-013-0132-z

Jones, M., Walker, C., Anderson, Z., and Thatcher, L. (2016). "Automatic detection of alpine ski turns in sensor data," in *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing Adjunct – UbiComp* (Heidelberg), 856–860.

Kranz, M., Möller, A., Hammerla, N., Diewald, S., Plötz, T., Olivier, P., et al. (2013). The mobile fitness coach: towards individualized skill assessment using personalized mobile devices. *Pervasive Mob. Comput.* 9, 203–215. doi: 10.1016/j.pmcj.2012.06.002

Martínez, A., Jahnel, R., Buchecker, M., Snyder, C., Brunauer, R., and Stöggl, T. (2019). Development of an automatic alpine skiing turn detection algorithm based on a simple sensor setup. *Sensors* 19:902. doi: 10.3390/s19040902

Müller, E., and Schwameder, H. (2003). Biomechanical aspects of new techniques in alpine skiing and ski-jumping. *J. Sports Sci.* 21, 679–692. doi: 10.1080/0264041031000140284

Nakazato, K., Scheiber, P., and Müller, E. (2011). A comparison of ground reaction forces determined by portable force-plate and pressure-insole systems in alpine skiing. *J. Sports Sci. Med.* 10, 754–762.

Reid, R. (2010). *A Kinematic and Kinetic Study of Alpine Skiing Technique in Slalom* (Doctoral dissertation). Norwegian School of Sport Sciences, Oslo, Norway.

Seel, T., Raisch, J., and Schauer, T. (2014). IMU-based joint angle measurement for gait analysis. *Sensors* 14, 6891–6909. doi: 10.3390/s140406891

Spörri, J., Kröll, J., Schwameder, H., and Müller, E. (2012). Turn characteristics of a top world class athlete in giant slalom: a case study assessing current performance prediction concepts. *Int. J. Sports Sci. Coach.* 7, 647–659. doi: 10.1260/1747-9541.7.4.647

Supej, M., Kugovnik, O., and Nemec, B. (2003). Kinematic determination of the beginning of a ski turn. *Kinesiol Slov*. 9, 11–17.

Supej, M., Sætran, L., Oggiano, L., Ettema, G., Šarabon, N., Nemec, B., et al. (2013). Aerodynamic drag is not the major determinant of performance during giant slalom skiing at the elite level. *Scand. J. Med. Sci. Sports* 23, e38–e47. doi: 10.1111/sms.12007

Ulrich, B., Fasel, B., Spörri, J., Müller, E., and Aminian, K. (2015). "Using inertial sensors to compute an alpine ski racing specific full body kinematic model–an application to track the distance between ankle joint and athlete's center of mass," in *7th Annual Congress of the Swiss Society of Sports Sciences* (Lausanne).

Yu, G., Jang, Y. J., Kim, J., Kim, J. H., Kim, H. Y., Kim, K., et al. (2016). Potential of IMU sensors in performance analysis of professional alpine skiers. *Sensors* 16:463. doi: 10.3390/s16040463

Conflict of Interest Statement: 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.

frontiers in Sports and Active Living

ORIGINAL RESEARCH
published: 05 November 2019
doi: 10.3389/fspor.2019.00055

Did the Relative Age Effect Change Over a Decade in Elite Youth Ski Racing?

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The relative age effect (RAE) represents an asymmetry in birth quarter distribution, favoring athletes born early in the selection year and discriminating against late born athletes. The RAE was proven to be present in all age categories of national and international levels of alpine ski racing. Due to the existence of the RAE in all categories, it can be assumed that a selection error takes place favoring early born and early maturing youth ski racers. However, whether selection strategies have changed during the last years due to the high amount of research done in this field, has not been investigated so far in this sport. Therefore, the aim of the present study was to assess whether the magnitude of the RAE in youth ski racers aged 10–14 years has changed during the last decade by comparing the periods 2005–2009 ("former" athletes) and 2015–2019 ("current" athletes). Pupils of a well-known skiing-specific secondary modern school as well as members of the provincial ski team, who all competed at national levels, were included in the study. Next to the birth months, anthropometric characteristics (body height, weight, body mass index) were assessed. Chi-square tests were used to compare differences between the observed and expected relative age quarter distributions across five age categories (U11–U15). Additionally, Kruskal–Wallis-*H*-Tests were performed to assess differences in anthropometric characteristics between athletes of the four relative age quarters. Mann–Whitney *U*-Tests were performed to assess possible differences in anthropometric characteristics between former and current ski racers. A highly significant RAE was present in both former [$\chi^2_{(3,\,764)} = 60.36$; $p < 0.001$; $\omega = 0.31$] and current youth ski racers [$\chi^2_{(3,\,702)} = 43.13$; $p < 0.001$; $\omega = 0.29$] with an over-representation of athletes of Q1 (30.3–34.2%) and a clear under-representation of athletes of Q4 (14.8–15.0%). Generally, results indicated no change in the magnitude of the RAE in youth alpine ski racing over the past 10–15 years, emphasizing the robust nature of this phenomenon. No significant differences were found in any of the anthropometric characteristics between athletes of the four relative age quarters in both former and current athletes, indicating that relatively younger athletes of the last relative age quarter seem to have to have advanced anthropometric characteristics for being selected. Changes in the talent selection process should be performed to reduce the impact of the RAE.

Keywords: ski racing, talent development, relative age quarter distribution, discrimination, selection error

OPEN ACCESS

Edited by:
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Balgrist University Hospital, Switzerland

Reviewed by:
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Specialty section:
This article was submitted to Sports Science, Technology and Engineering, a section of the journal Frontiers in Sports and Active Living

Received: *14 August 2019*
Accepted: *16 October 2019*
Published: *05 November 2019*

Citation:
Steidl-Müller L, Müller E, Hildebrandt C and Raschner C (2019) Did the Relative Age Effect Change Over a Decade in Elite Youth Ski Racing? Front. Sports Act. Living 1:55. doi: 10.3389/fspor.2019.00055

INTRODUCTION

The *relative age effect* (RAE) represents a well-documented phenomenon in youth sports context, and was first documented in Canadian ice hockey (Barnsley et al., 1985). It exists when the relative age quarter distribution of selected athletes represents a biased distribution with an over-representation of athletes born early in the selection year, meaning close to the cut-off date for the competition categories (Musch and Grondin, 2001). Even though the intention of grouping children and youth athletes into competition categories based on their chronological age is to guaranteeing fair competition and reflecting age-related development, age differences of up to 12 months are possible between athletes competing in the same category. These relative age advantages are defined as the RAE; its presence has been proven in several different types of sport, such as soccer (Helsen et al., 2005; Cobley et al., 2009; Romann and Fuchslocher, 2013), ice hockey (Hurley et al., 2001), basketball (Delorme and Raspaud, 2009), volleyball (Nakata and Sakamoto, 2013), baseball (Nakata and Sakamoto, 2012), swimming (Medic et al., 2009), tennis (Edgar and O'Donoghue, 2005), among others. Talent selection systems are often based on selection biases that confuse maturation for talent (Baker et al., 2014). In this context, Baker et al. (2014) proposed the *maturation-hypothesis* for explaining the RAE, assuming that the relative age of an athlete is related to the athlete's cognitive and physical maturation. Thus, maturational differences between relatively older and relatively younger athletes seem to influence the favorable selection of the relatively older ones (Baker et al., 2014). As a short-term consequence, relatively older and more mature athletes seem to be potentially more "talented," which leads to the favorable selection of them, whereas relatively younger and less mature athletes are often over-looked and do not get the same changes for fulfilling their potential (Malina et al., 2004; Romann and Cobley, 2015). Knowing that talent in a sport does not depend on the birth month, the existence of the RAE indicates that the talent development systems in these sports are biased and that many young talented athletes are discriminated against (Lames et al., 2008; Cobley et al., 2009).

The RAE is present also in alpine ski racing at both national and international levels. It starts to exist at the youngest age groups of national levels with athletes aged 7–11 years (Müller et al., 2015a), continuing on national levels with athletes aged up to 14 and 15 years (Romann and Fuchslocher, 2014; Müller et al., 2015a). At international youth and adolescent levels, the RAE is present among ski racers participating at the International Children's Games (12–15 years; Müller et al., 2017b), the European Youth Olympic Festival (17–18 years; Müller et al., 2016a), the Youth Olympic Games (15–16 years; Raschner et al., 2012), as well as the Junior World Ski Championships (16–20 years; Müller et al., 2012). At elite level, the RAE is also present among World Cup athletes (Müller et al., 2012; Baker et al., 2014; Bjerke et al., 2016). At most age categories and levels, the RAE exists among both male and female athletes (Steidl-Müller et al., 2019). The likelihood for selection for national final races among 10–12 year old youth ski racers is up to 3.4 times higher for an athlete born in the first 3 months of the year compared with an athlete born between July and September and even 5.1 times higher compared with an athlete born in the last 3 months (Müller et al., 2017a). The biological maturation additionally influences the selection process in youth ski racing because relatively younger athletes, meaning athletes born late in the selection year, seem to "only" have a chance for selection for national final races if they are early maturing. More than 40% of the selected ski racers for the national final races born in the last quarter were early maturing, whereas in an age-matched comparison group of non-athletes a normal distribution of early, normal, and late maturing pupils was found in each quarter (Müller et al., 2017a). Additionally, hardly any late maturing ski racers were found in the cohort of selected athletes for national final races in general independent of their relative age quarter (Müller et al., 2017a). Thus, selection processes in youth alpine ski racing are influenced by the relative age and the biological maturation of an athlete; a fact which leads to the necessity of changes in the talent development systems in order to guarantee more fairness for all athletes independent of their relative age and biological maturity status (Steidl-Müller et al., 2019).

Research has focused on the RAE and the influential mechanisms of it during the last years. Several solutions were proposed to minimize the effect, such as rotating cut-off dates (Hurley et al., 2001), changing cut-off dates (Cobley et al., 2009), implementing corrective adjustments (Romann and Cobley, 2015) etc. However, thus far, the effectiveness of these suggestions has not been proven (Romann and Fuchslocher, 2014). Whether the extent of the RAE has changed during the last years after the research focus on it in several types of sport was investigated only in European soccer. Helsen et al. (2012) examined whether 10 years of research has made any difference in the RAE in professional soccer in ten European countries and did not find any changes in the occurrence and strength of the RAE after 10 years (2000/2001 season vs. 2010/2011 season) indicating the robust nature of this phenomenon. However, whether the extent of the RAE in alpine ski racing has changed after the first research studies in 2012 (Müller et al., 2012) and later on, has not been investigated, so far.

Ski boarding schools play an important role in the talent development in ski racing in Austria. The schools concentrate on the dual career of the athletes combining school and sport. Next to the schools, the provincial ski teams represent a serious cornerstone in the development of young talents in this sport (Raschner et al., 2015). The social significance of alpine ski racing in Austria is reflected in the high number of young athletes starting with this sport already at the age of 5–6 years; up to 200 athletes per birth year compete in children's races at this age. Based on these numbers, not surprisingly, a high selection pressure is present in this sport in Austria and the first selection already takes place as early as the age of 9–10 years, when the entrance exams for ski boarding schools are held, as well as at the age of 12–13 years for the teenager squad of the provincial ski teams (Raschner et al., 2015). The awareness of the RAE problem has increased during the last years among coaches of the boarding schools and the provincial ski teams, but it is not clear whether the research output had also affected the selection processes in this sport. Therefore, the aim of the present study

TABLE 1 | Number (*n*) of participants per age group divided by former (2005–2009) and current (2015–2019) period.

Sample	Age category	2005–2009	2015–2019
Total sample	U11	68	36
	U12	140	151
	U13	178	235
	U14	201	116
	U15	177	164
Males	U11	38	23
	U12	83	76
	U13	94	130
	U14	111	67
	U15	102	94
Females	U11	30	13
	U12	57	75
	U13	84	105
	U14	90	49
	U15	75	70

was to assess whether the magnitude of the RAE in youth ski racers aged 10–14 years has changed during the last decade by comparing the periods 2005–2009 ("former" athletes) and 2015–2019 ("current" athletes). It was hypothesized that the magnitude of the RAE may have diminished during the last decade due to the greater awareness of the consequence of this selection bias.

MATERIALS AND METHODS

Participants

In the present study, elite youth ski racers, who all competed in ski races at national level, were included. They were pupils of well-known Austrian skiing-specific secondary modern schools or members of the provincial ski team. The ski racers can be divided into two groups: 764 participants (428 male, 336 female) tested from 2005 to 2009, and 702 participants (390 male, 312 female) tested 10 years later (2015–2019). The athletes ranged in age between 9.6 and 14.5 years (mean age: 12.5 ± 1.2 years). To minimize effects of one single season, each 5 consecutive years were summarized per age group (U11–U15) and subsequently defined as "former" (2005–2009) and "current" (2015–2019) period. **Table 1** presents the number of participants per age group divided by the two 5-year periods (2005–2009 vs. 2015–2019) and per gender.

Procedures

The procedures are in accordance with the ethical standards of the Declaration of Helsinki and were approved by the Institutional Review Board. The birth dates of all participants were collected prior to the assessment of the anthropometric characteristics. The birth months were then categorized into four relative age quarters. In alpine ski racing in Austria, the cut-off date for the competition categories is January 1. Therefore, the birth months were split into quarters to calculate the relative age quarters as follows: January to March was categorized as relative age quarter 1 (Q1); April to June as quarter 2 (Q2); July to September as quarter 3 (Q3), and October to December as quarter 4 (Q4).

The anthropometric characteristics were assessed at the end of the winter season in April or May of the single calendar year. The body height (0.5 cm) was recorded using a portable stadiometer SECA 217 (Seca, Hamburg, Germany). Body mass (1 N) was measured on a Kistler force plate (Kistler Instrumente AG, Gommiswald, Switzerland) with normal sports clothes but without shoes, and was then calculated to the nearest 0.1 kg (divided by 9.81). The body mass index (BMI; 0.1 kg/m²) was then calculated as body mass in kilograms divided by height in meter squared (Nuttall, 2015).

Statistical Analyses

To assess the difference between the observed and the expected relative age quarter distributions, chi²-tests (χ^2) were used for the former (2005–2009) and current (2015–2019) youth ski racers. The relative age quarter distribution of the Austrian population of the same birth years as the participants, which corresponded to a nearly even distribution among the four quarters (nearly 25% in each quarter), was used as the expected distribution for these analyses. The effect size ω was calculated for the χ^2-tests (Sherar et al., 2007). Odds ratio (OR) and 95% confidence intervals (95% CI) were calculated (Cobley et al., 2009). Additionally, χ^2-tests and the corresponding Cramer's *V* were also used to assess differences in the birth quarter distributions between the former (2005–2009) and current (2015–2019) youth ski racers over all age categories, as well as for each age group separately. All analyses were performed for the total sample of the two 5-year periods as well as separated by gender. In order to assess possible differences in the anthropometric characteristics between the four relative age quarters, Kruskal–Wallis-*H*-Tests were performed (due to small sample sizes in each category) for each age category as well as separated by the two 5-year periods. Additionally, possible differences in the anthropometric characteristics between former and current athletes were assessed using Mann–Whitney *U*-Tests separated by relative age quarter, age category, and gender.

The level of significance was set at $p < 0.05$. All of the calculations were performed using IBM SPSS 25.0 (IBM Corporation, Armonk, NY, USA); the effect size ω was assessed using G*Power 3.1.9.2 (University of Düsseldorf, Germany).

RESULTS

Presence of the Relative Age Effect

A highly significant RAE was found for both former [$\chi^2_{(3, 764)} = 60.36$; $p < 0.001$; $\omega = 0.31$) and current youth ski racers [$\chi^2_{(3, 702)} = 43.13$; $p < 0.001$; $\omega = 0.29$] with an over-representation of athletes of Q1 and a clear under-representation of athletes of Q4 (14.8–15.0%). The distribution of the male athletes of both groups significantly differed from the expected distribution as well [former: $\chi^2_{(3, 428)} = 34.22$; $p < 0.001$; $\omega = 0.32$; current: $\chi^2_{(3, 390)} = 34.57$; $p < 0.001$; $\omega = 0.39$] with larger effect sizes in the current group. The relative age quarter distribution of the female athletes significantly differed from the expected

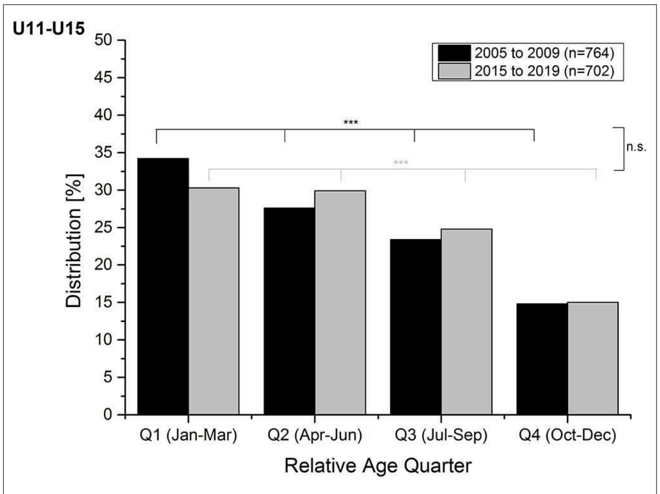

FIGURE 1 | Relative age quarter distributions of former (2005–2009; black) and current (2015–2019; light gray) ski racers of all age groups (U11–U15). ***p < 0.001; n.s., not significant difference between groups.

distribution in both groups, as well [former: $\chi^2_{(3, 336)} = 26.36$; $p < 0.001$; $\omega = 0.31$; current: $\chi^2_{(3, 312)} = 13.10$; $p = 0.004$; $\omega = 0.21$] with larger effect sizes in the former group of athletes. The relative age quarter distributions of the total sample of former (2005–2009) and current (2015–2019) athletes are presented in **Figure 1**. **Table 2** presents the distributions of both 5-year periods for the different age groups and separated by gender. The descriptive OR and the corresponding χ^2 for each quarter of the total sample and both male and female athletes of the former and the current ski racer groups are presented in **Table 3**. With respect to the former ski racers (2005–2009), the OR calculations revealed significant differences between Q1 and all other quarters in the total sample as well as between Q1 and Q3 and Q4 in the male athletes and between Q1 and Q4 in the female athletes. The calculations revealed additionally, that among the current ski racers (2015–2019), differences were found between Q1 and Q3 and Q4 in the total sample, as well as between Q1 and Q4 in both male and female athletes and between Q1 and Q3 in female athletes. The likelihood of selection for the ski boarding school or the provincial ski teams was up to 2.50 times higher for an athlete of Q1 compared with an athlete of Q4 in the current group and up to 2.35 times higher in the former group.

Changes in the Relative Age Effect Over the Decade

The relative age distribution of the current ski racer group did not significantly differ from the distribution of the former group of athletes neither in the total sample nor in male or female athletes (see **Table 2**). When separating by age group, a significant difference was found in the U12 age group of the total sample (see **Figure 2**), showing a stronger RAE in the former athletes ($V = 0.17$). Among male athletes, significant differences between relative age quarter distributions of the former and the current youth ski racers were evident in the U11 and U13 age groups with a stronger RAE in the former U11 athletes ($V = 0.40$) and a stronger RAE in current U13 ski racers ($V = 0.24$). Similar results were found among female athletes: significant differences in the relative age quarter distributions were present in U11 (stronger RAE of current athletes; $V = 0.46$) and U12 (stronger RAE among former athletes; $V = 0.29$).

Differences in Anthropometric Characteristics Between Relative Age Quarters

The anthropometric characteristics of former (2005–2009) and current (2015–2019) youth ski racers of the four relative age quarters are presented separated by age group for male athletes in **Table 4** and for female athletes in **Table 5**. No significant differences were found in any of the three anthropometric characteristics as well as in any age group between the athletes of the four relative age quarters neither in the former athletes nor in the current athletes. Significant differences between former and current male ski racers were found in body height in the U12 age group of athletes born in Q2 ($z = -2.222$; $p = 0.026$), in body weight in U14 athletes of Q1 ($z = -2.038$; $p = 0.042$) and in BMI in U14 ($z = -2.659$; $p = 0.008$) and U15 athletes of Q1 ($z = -2.092$; $p = 0.036$). In female athletes significant differences between former and current athletes were found in body weight in U12 athletes of Q4 ($z = -2.552$; $p = 0.011$) and in BMI in U12 athletes of Q4 ($z = -2.130$; $p = 0.033$) and in U13 athletes of Q2 ($z = -2.059$; $p = 0.039$).

DISCUSSION

The present study was the first study that assessed the longitudinal development of the magnitude of the RAE in youth alpine ski racing. In both groups of selected athletes, former and current ski racers, and among both males and females, a highly significant RAE was found. No significant change in the magnitude of the RAE was evident when comparing former and current youth ski racers in total or divided by gender and age category. Only in U12 athletes, a weaker RAE was assessed among current athletes.

Due to the importance of the two cornerstones in the talent development in youth ski racing (ski boarding schools and provincial ski teams), selected athletes of both organizations were included in the present study. Due to the high selection pressure, not surprisingly, a significant RAE was found in male and female former and current youth ski racers, which is in line with several studies assessing the RAE in youth alpine ski racing (Steidl-Müller et al., 2019). There has been neither a decrease nor an increase in the prevalence of the RAE over a decade ($p > 0.05$). The relative age quarter distribution showed that 30.3% of the current athletes were born in the first quarter and only 15.0% were born in the last quarter, compared with 34.2 and 14.8%, respectively in former athletes. Additionally, similar effect sizes were calculated for both groups (former: $\omega = 0.31$; current: $\omega = 0.29$). When differentiating by gender, similar results were found showing no significant change in the prevalence of the RAE in both males and females ($p > 0.05$). However, in male athletes a stronger effect size was evident in the current athletes ($\omega = 0.39$

TABLE 2 | Relative age quarter distributions of male and female former (2005–2009) and current (2015–2019) youth ski racers.

		Period	*n*	Q1 [%]	Q2 [%]	Q3 [%]	Q4 [%]	Diff. 2005–2009 vs. 2015–2019		
								χ^2	*p*	Cramer's *V*
Total sample	Total	2005–2009	764	34.2	27.6	23.4	14.8	2.61	0.456	0.04
		2015–2019	702	30.3	29.9	24.8	15.0			
	U11	2005–2009	68	20.6	30.9	33.8	14.7	4.21	0.239	0.20
		2015–2019	36	8.3	47.2	27.8	16.7			
	U12	2005–2009	140	34.3	27.9	26.4	11.4	8.73	**0.033**	0.17
		2015–2019	151	28.5	26.5	20.5	24.5			
	U13	2005–2009	178	32.6	27.5	23.6	16.3	7.17	0.067	0.13
		2015–2019	235	36.2	32.8	23.0	8.1			
	U14	2005–2009	201	34.8	28.4	19.9	16.9	3.15	0.369	0.10
		2015–2019	116	31.0	24.1	28.4	16.4			
	U15	2005–2009	177	40.1	25.4	20.9	13.6	5.93	0.115	0.13
		2015–2019	164	28.0	29.3	28.0	14.6			
Males	Total	2005–2009	428	34.1	27.3	24.1	14.5	2.61	0.456	0.06
		2015–2019	390	30.8	29.7	27.2	12.3			
	U11	2005–2009	38	23.7	42.1	34.2	0	9.85	**0.020**	0.40
		2015–2019	23	13.0	43.5	21.7	21.7			
	U12	2005–2009	83	36.1	27.7	22.9	13.3	2.06	0.561	0.11
		2015–2019	76	26.3	30.3	25.0	18.4			
	U13	2005–2009	94	30.9	25.5	24.5	19.1	12.75	**0.005**	0.24
		2015–2019	130	40.8	30.8	23.8	4.6			
	U14	2005–2009	111	35.1	24.3	21.6	18.9	4.53	0.210	0.16
		2015–2019	67	28.4	22.4	35.8	13.4			
	U15	2005–2009	102	38.2	26.5	23.5	11.8	3.09	0.378	0.13
		2015–2019	94	26.6	29.8	28.7	14.9			
Females	Total	2005–2009	336	34.2	28.0	22.6	15.2	2.22	0.528	0.06
		2015–2019	312	29.8	30.1	21.8	18.3			
	U11	2005–2009	30	16.7	16.7	33.3	33.3	9.06	**0.029**	0.46
		2015–2019	13	0	53.8	38.5	7.7			
	U12	2005–2009	57	31.6	28.1	31.6	8.8	11.17	**0.011**	0.29
		2015–2019	75	30.7	22.7	16.0	30.7			
	U13	2005–2009	84	34.5	29.8	22.6	13.1	0.69	0.875	0.06
		2015–2019	105	30.5	35.2	21.9	12.4			
	U14	2005–2009	90	34.4	33.3	17.8	14.4	1.16	0.762	0.09
		2015–2019	49	34.7	26.5	18.4	20.4			
	U15	2005–2009	75	42.7	24.0	17.3	16.0	3.53	0.317	0.16
		2015–2019	70	30.0	28.6	27.1	14.3			

Q, relative age quarter; Q1, January–March; Q2, April–June; Q3, July–September; Q4, October–December. Bold values highlight significant differences in the relative age quarter distributions between former and current youth ski racers.

vs. $\omega = 0.32$), whereas among the female ski racers a weaker effect size was calculated in the current youth ski racer group ($\omega = 0.21$ vs. $\omega = 0.31$). However, in both males and females an over-representation of athletes of Q1 and a clear under-representation of athletes of Q4 was evident. These results are in line with the comparison of the prevalence of the RAE between 2000/2001 and 2010/2011 elite European soccer players, in which no significant change was found (Helsen et al., 2012). Despite the great research interest and the proposed solutions to minimize the RAE, there has been little impact on the effect (Helsen et al., 2012). Only in the U12 age category a significant decrease in the prevalence of the RAE was found in the total sample of male and female ski racers over the decade. However, the fact that in the next age group (U13) an obviously stronger RAE was present again in the current group compared with the former U13 group, but also compared with the U12 current group, leads to the speculation that the selection for the provincial ski teams, which takes place at the age of approximately 12 years, might clearly favor relatively older athletes during the last 5 years and therefore, might strengthen again the RAE. Though, when comparing the distributions of the male and female current and former athletes separately, different trends are apparent. A significant weaker RAE was found in male U11 athletes of the current group ($V = 0.40$), whereas in the females a stronger RAE was present

TABLE 3 | Descriptive odds ratio across all relative age quarters of former (2005–2009) and current (2015–2019) youth ski racers.

Sample		Q1:Q2		Q1:Q3		Q1:Q4	
		2005–2009	2015-2019	2005-2009	2015-2019	2005–2009	2015–2019
Total sample	Chi²	5.30	0.02	15.28	3.93	58.57	36.68
	p value	0.021	0.884	<0.001	0.047	<0.001	<0.001
	OR [95% CI]	**1.24 (1.09–1.41)**	1.02 (0.88–1.15)	**1.46 (1.27–1.67)**	**1.22 (1.06–1.41)**	**2.31 (1.95–2.73)**	**2.03 (1.70–2.42)**
Male athletes	Chi²	3.20	0.07	7.43	0.87	33.92	30.86
	p value	0.074	0.795	0.006	0.352	<0.001	<0.001
	OR [95% CI]	**1.25 (1.05–1.48)**	1.03 (0.86–1.24)	**1.42 (1.18–1.70)**	1.31 (0.94–1.36)	**2.35 (1.88–2.95)**	**2.50 (1.93–3.23)**
Female athletes	Chi²	2.11	0.00	0.87	3.88	24.68	8.64
	p value	0.146	0.942	0.352	0.049	<0.001	0.003
	OR [95% CI]	**1.22 (1.01–1.48)**	0.99 (0.81–1.21)	**1.51 (1.23–1.87)**	**1.37 (1.09–1.71)**	**2.25 (1.76–2.90)**	**1.63 (1.28–2.07)**

OR, odds ratio; CI, Confidence Interval; Q1–4, relative age quarter 1–4. Bolded values indicate significance of odds ratio (if 95% CI does not include 1).

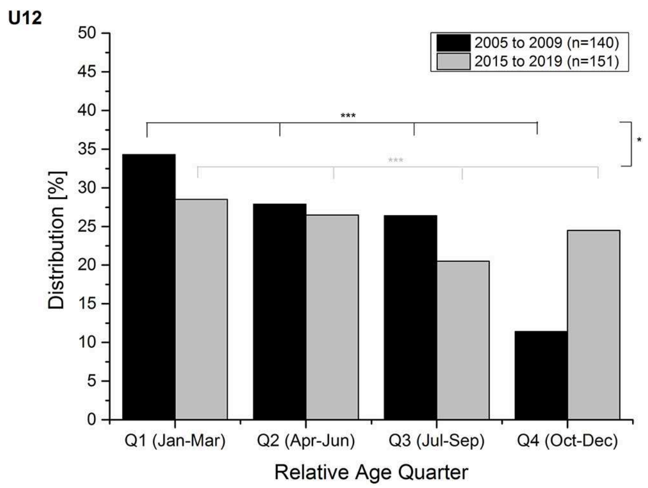

FIGURE 2 | Changes in the relative age quarter distributions of former (black) to current (light gray) U12 youth ski racers. ***$p < 0.001$; *$p < 0.05$.

in the current group ($V = 0.46$). However, the small sample sizes have to be considered in the U11 age groups (males: 38 vs. 23; females: 30 vs. 13). Conversely, in female U12 athletes a weaker RAE was present in the current group ($V = 0.29$), whereas in male U13 athletes a stronger RAE was evident in the current group ($V = 0.24$). One might speculate that nowadays young girls enter puberty even earlier than it might have been a decade ago, which could probably explain why the RAE, which is much influenced by the maturation-based selection, was stronger in the current U11 group, but was weaker in the current U12 group. In the study performed by Helsen et al. (2012), elite soccer players were investigated, thus, no age categories were considered in the analyses, which does not allow any comparisons, though.

The most frequent explanation for the RAE phenomenon is the maturation-selection hypothesis (Baker et al., 2014), which was confirmed also in youth alpine ski racing showing that the most valuable influential factor of the RAE seems to be the biological maturity status (Steidl-Müller et al., 2019). Relatively younger athletes seem to "only" have a chance for selection if they are early maturing, which was confirmed by the findings that 43% of athletes born in Q4 who were selected for national final races (11–12 years) were early maturing (Müller et al., 2017a), a finding which was observed also in youth soccer (Deprez et al., 2013) and basketball (Torres-Unda et al., 2013), as well. Additionally, youth ski racers of the last relative age quarter that were selected for national final races significantly differed in biological maturity status from Q4-athletes that were not selected in both males and females (Müller et al., 2016b). In alpine ski racing an advanced biological maturity status is advantageous in the selection process because more mature athletes benefit from early recognition from coaches and talent scouts (Müller et al., 2017a). Based on this assumption, relatively younger athletes can counteract their relative age disadvantage by an advanced maturation and thus, it can be assumed that they represent similar or more advanced anthropometric characteristics compared with the athletes of the other relative age quarters. The biological maturity status was not measured in the present study, because the implementation of the prediction of the age at peak height velocity (APHV; Mirwald et al., 2002) in the regular fitness testing of youth ski racers was conducted starting in 2015 onwards; however, the prediction of the APHV is based on anthropometric measurements (Mirwald et al., 2002) and anthropometric characteristics such as body height and weight correlate with the biological maturation. Thus, in the present study anthropometric characteristics were compared between athletes of the four relative age quarters in both former and current ski racers. In contrast to the study of Müller et al. (2015b), in which youth ski racers born in Q1 had significantly higher values in body height and weight, no significant differences were found in anthropometric characteristics between the four relative age quarters in both former and current ski racers. Thus, it can be assumed that the ski racers of the four relative age quarters were comparable with respect to their maturation, a finding which would be in line with previous studies including the measurement of the biological maturation and showing no differences between athletes of the four relative age quarters (Müller et al., 2015b, 2016b, 2017a). Similar results were found also in studies in soccer, in which

TABLE 4 | Anthropometric characteristics (M ± SD) and inferential statistics of former (2005–2009) and current (2015–2019) male youth ski racers divided by relative age quarter.

		Q1 (Jan-Mar)	Q2 (Apr-June)	Q3 (July-Sept)	Q4 (Oct-Dec)	Kruskal–Wallis H	*p*
Body height [cm]							
U11	2005–2009 ($n = 38$)	140.2 ± 5.5	142.6 ± 6.2	143.5 ± 4.8	x	1.33	0.515
	2015–2019 ($n = 23$)	147.7 ± 6.0	140.6 ± 5.9	142.2 ± 4.8	145.9 ± 6.9	4.54	0.209
U12	2005–2009 ($n = 83$)	146.8 ± 6.2	148.9 ± 7.1	146.7 ± 5.9	146.6 ± 9.1	1.95	0.582
	2015–2019 ($n = 76$)	146.5 ± 4.9	144.8 ± 4.9	145.5 ± 5.0	148.9 ± 5.0	5.62	0.132
U13	2005–2009 ($n = 94$)	153.3 ± 7.6	152.6 ± 6.0	151.7 ± 6.8	150.6 ± 7.5	1.54	0.673
	2015–2019 ($n = 130$)	152.8 ± 5.4	151.0 ± 6.0	150.4 ± 5.8	149.7 ± 7.7	5.15	0.161
U14	2005–2009 ($n = 111$)	159.6 ± 8.3	157.5 ± 7.3	157.4 ± 9.2	155.4 ± 8.0	3.53	0.317
	2015–2019 ($n = 67$)	157.6 ± 7.1	158.3 ± 6.8	159.0 ± 8.8	156.6 ± 3.6	0.35	0.950
U15	2005–2009 ($n = 102$)	166.0 ± 8.3	166.3 ± 9.2	166.3 ± 9.0	163.4 ± 10.3	0.70	0.873
	2015–2019 ($n = 94$)	166.0 ± 8.0	166.5 ± 7.1	166.5 ± 8.1	168.9 ± 8.6	0.81	0.846
Body weight [kg]							
U11	2005–2009 ($n = 38$)	34.8 ± 4.2	34.6 ± 6.0	37.2 ± 6.0	x	1.17	0.556
	2015–2019 ($n = 23$)	38.5 ± 8.8	32.5 ± 3.9	35.3 ± 5.8	39.7 ± 7.3	3.83	0.281
U12	2005–2009 ($n = 83$)	37.6 ± 5.9	40.6 ± 7.5	40.3 ± 7.2	38.6 ± 8.6	2.26	0.520
	2015–2019 ($n = 76$)	37.6 ± 5.6	36.5 ± 4.0	37.8 ± 5.1	38.5 ± 3.5	2.32	0.509
U13	2005–2009 ($n = 94$)	43.0 ± 6.3	42.3 ± 6.3	43.0 ± 7.9	41.6 ± 7.3	1.22	0.748
	2015–2019 ($n = 130$)	42.2 ± 4.8	41.0 ± 5.7	42.7 ± 7.5	39.3 ± 5.1	1.92	0.589
U14	2005–2009 ($n = 111$)	49.1 ± 8.2	46.5 ± 6.4	47.6 ± 8.4	46.1 ± 7.6	2.91	0.405
	2015–2019 ($n = 67$)	44.3 ± 5.9	45.1 ± 7.3	50.6 ± 10.9	44.5 ± 5.0	3.85	0.278
U15	2005–2009 ($n = 102$)	55.4 ± 7.6	56.6 ± 9.4	54.9 ± 9.4	52.7 ± 9.9	1.91	0.590
	2015–2019 ($n = 94$)	53.2 ± 7.8	54.7 ± 9.3	56.9 ± 9.9	55.0 ± 9.1	1.22	0.749
Body mass index [kg*m^{-2}]							
U11	2005–2009 ($n = 38$)	18.1 ± 1.4	16.9 ± 2.4	18.1 ± 2.2	x	4.30	0.116
	2015–2019 ($n = 23$)	17.5 ± 3.7	16.4 ± 1.2	17.4 ± 2.1	18.5 ± 1.8	3.92	0.270
U12	2005–2009 ($n = 83$)	17.6 ± 1.7	18.0 ± 2.4	18.7 ± 2.4	17.7 ± 2.0	2.46	0.483
	2015–2019 ($n = 76$)	17.5 ± 2.1	17.3 ± 1.5	17.8 ± 2.0	17.4 ± 1.1	0.97	0.808
U13	2005–2009 ($n = 94$)	18.3 ± 1.8	18.1 ± 2.0	18.7 ± 2.4	18.2 ± 1.7	0.62	0.893
	2015–2019 ($n = 130$)	18.1 ± 1.8	17.9 ± 1.7	18.8 ± 2.3	17.6 ± 0.9	4.04	0.257
U14	2005–2009 ($n = 111$)	19.2 ± 1.7	18.7 ± 1.5	19.2 ± 2.1	19.0 ± 1.6	1.12	0.773
	2015–2019 ($n = 67$)	17.8 ± 1.5	18.0 ± 1.9	19.9 ± 2.7	18.1 ± 1.6	7.51	0.057
U15	2005–2009 ($n = 102$)	20.0 ± 1.7	20.3 ± 1.7	19.8 ± 1.9	19.7 ± 2.1	2.18	0.537
	2015–2019 ($n = 94$)	19.3 ± 1.9	19.6 ± 2.1	20.4 ± 2.4	19.2 ± 1.8	4.92	0.178

no differences in the biological maturity status between athletes of the four relative age quarters were evident (Gil et al., 2014; Lovell et al., 2015). As a consequence, it can be speculated that relatively younger athletes of the fourth relative age quarter are more mature when they have the same anthropometric characteristics as athletes who are some months older. Even though it only can be speculated because the biological maturity status was not measured, it might underline the supposed necessity of advanced anthropometric characteristics of relatively younger ski racers for getting the possibility of being selected irrespective of their relative age disadvantage. And due to the performance advantages of advanced anthropometric characteristics in alpine ski racing (Raschner et al., 1995), it can be hypothesized that this could partly explain why both former and current ski racers of the four relative age quarters did not differ in anthropometric characteristics between each other. In general, former and current male and female ski racers did not significantly differ in anthropometric characteristics without differentiating between quarters. Only among athletes of single quarters and age categories differences were found. However, whether for example the higher body mass in current female athletes of Q4 in the U12 age group has led to the reduced prevalence of the RAE in the current group can only be speculated. Nevertheless, all these results emphasize the favorable selection of relatively older and more mature athletes in ski racing and this has not changed during the last decade.

However, it has to be considered that the selection of the participants for this study was performed in that way that all youth ski racers who were either pupils of the skiing-specific boarding schools or members of the provincial ski team in the given periods were included. This has to be seen as limitation of the study, because the study did not include all athletes that competed at national levels in this period. Another limitation

TABLE 5 | Anthropometric characteristics (M ± SD) and inferential statistics of former (2005–2009) and current (2015–2019) female youth ski racers divided by relative age quarter.

		Q1 (Jan-Mar)	Q2 (Apr-June)	Q3 (July-Sept)	Q4 (Oct-Dec)	Kruskal–Wallis H	*p*
Body height [cm]							
U11	2005-2009 (*n* = 30)	145.2 ± 4.0	142.8 ± 4.6	139.6 ± 7.2	139.7 ± 5.1	6.87	0.076
	2015–2019 (*n* = 13)	x	142.2 ± 4.6	140.8 ± 3.7	144.0	0.72	0.697
U12	2005–2009 (*n* = 57)	145.6 ± 8.2	145.5 ± 6.3	144.8 ± 7.4	143.5 ± 2.9	2.24	0.525
	2015–2019 (*n* = 75)	146.3 ± 6.0	145.3 ± 4.1	146.2 ± 5.5	148.4 ± 7.5	2.98	0.395
U13	2005–2009 (*n* = 84)	152.6 ± 7.7	152.9 ± 7.6	149.1 ± 5.2	152.4 ± 8.6	5.22	0.156
	2015–2019 (*n* = 105)	154.1 ± 6.3	152.0 ± 5.9	150.6 ± 6.2	152.3 ± 6.4	3.85	0.278
U14	2005–2009 (*n* = 90)	157.5 ± 7.3	158.6 ± 5.9	155.8 ± 5.5	160.2 ± 6.1	3.32	0.345
	2015–2019 (*n* = 49)	160.9 ± 6.6	159.6 ± 4.4	158.7 ± 7.7	158.3 ± 7.8	1.04	0.792
U15	2005–2009 (*n* = 75)	161.4 ± 5.1	163.0 ± 5.7	162.3 ± 5.8	165.3 ± 5.1	4.89	0.180
	2015–2019 (*n* = 70)	163.5 ± 5.5	164.1 ± 4.1	163.0 ± 6.8	161.0 ± 4.9	2.78	0.426
Body weight [kg]							
U11	2005–2009 (*n* = 30)	33.8 ± 3.0	37.3 ± 4.5	32.5 ± 4.6	31.5 ± 1.7	3.59	0.309
	2015–2019 (*n* = 13)	x	33.7 ± 3.0	32.3 ± 4.0	37.4	1.79	0.409
U12	2005–2009 (*n* = 57)	38.9 ± 7.2	37.6 ± 5.3	35.1 ± 5.1	34.1 ± 2.4	4.67	0.197
	2015–2019 (*n* = 75)	37.0 ± 4.5	36.3 ± 4.6	36.0 ± 5.4	39.8 ± 5.0	7.25	0.064
U13	2005–2009 (*n* = 84)	43.9 ± 7.2	44.5 ± 7.8	39.2 ± 4.4	43.0 ± 8.1	7.33	0.062
	2015–2019 (*n* = 105)	43.4 ± 6.1	41.3 ± 6.4	41.3 ± 5.4	43.0 ± 6.3	2.71	0.438
U14	2005–2009 (*n* = 90)	49.9 ± 8.5	49.7 ± 7.6	45.1 ± 4.6	51.3 ± 6.9	6.72	0.081
	2015–2019 (*n* = 49)	51.0 ± 7.8	49.5 ± 7.1	45.6 ± 4.1	50.7 ± 9.1	2.57	0.464
U15	2005–2009 (*n* = 75)	53.4 ± 7.3	54.9 ± 5.9	51.5 ± 4.8	56.3 ± 7.4	4.23	0.240
	2015–2019 (*n* = 70)	56.1 ± 8.0	55.2 ± 5.7	55.2 ± 7.3	55.9 ± 9.7	0.15	0.985
Body mass index [kg*m^{-2}]							
U11	2005–2009 (*n* = 30)	16.3 ± 0.0	18.0 ± 1.5	16.6 ± 1.5	16.5 ± 1.0	2.76	0.431
	2015–2019 (*n* = 13)	x	16.6 ± 1.0	16.2 ± 1.2	18.0	2.33	0.312
U12	2005–2009 (*n* = 57)	17.8 ± 1.6	17.6 ± 1.6	16.8 ± 1.4	16.6 ± 1.0	6.00	0.112
	2015–2019 (*n* = 75)	17.3 ± 1.5	17.2 ± 1.6	16.8 ± 1.6	18.1 ± 1.4	7.31	0.063
U13	2005–2009 (*n* = 84)	18.8 ± 1.9	18.9 ± 1.9	17.6 ± 1.4	18.5 ± 2.4	5.09	0.166
	2015–2019 (*n* = 105)	18.2 ± 1.7	17.8 ± 1.9	18.2 ± 1.4	18.5 ± 1.9	2.97	0.396
U14	2005–2009 (*n* = 90)	20.1 ± 2.6	19.7 ± 2.3	18.6 ± 1.4	20.1 ± 2.2	4.85	0.183
	2015–2019 (*n* = 49)	19.7 ± 2.4	19.4 ± 2.4	18.4 ± 1.5	20.1 ± 2.2	2.95	0.399
U15	2005–2009 (*n* = 75)	20.5 ± 2.5	20.7 ± 2.0	19.6 ± 1.8	20.6 ± 2.6	2.57	0.462
	2015–2019 (*n* = 70)	21.0 ± 2.6	20.5 ± 2.0	20.8 ± 2.2	21.5 ± 2.7	1.28	0.733

of the study is that one athlete could have been included in several age categories, which might represent a bias. However, the analyses were performed for each age category separately, and the information if an athlete drops out of sport at a given time point and is not again included in the next age category seems also important.

CONCLUSION

The magnitude of the RAE in youth alpine ski racing has not changed over the last 10–15 years. Despite the great research interest in this field and the proposed solutions to minimize the RAE, there has been little impact on the effect, as it was also the case in soccer (Helsen et al., 2012). Several suggestions to reduce the RAE, such as corrective adjustments or delaying the selection process of talent identification beyond stages of puberty and maturation (Cobley et al., 2009), do not seem applicable in alpine ski racing due to the changing outdoor environment that does not provide the possibility of calculating fair corrective adjustments as it is possible in swimming, or the early-specialization character of this sport (Steidl-Müller et al., 2019). As proposed in a recent review article (Steidl-Müller et al., 2019), changes in the competition system, as for example introducing a rotating cut-off date, seem to possibly be most effective for reducing the RAE. In addition, even though the awareness of the RAE problem has risen among coaches in youth ski racing during the last years, it does not seem to have changed selection criteria. As a consequence, the extent and the consequences of the RAE and the favorable selection of early born and early maturing ski racers should be spread even more during the education of coaches working with youth athletes. The long-term consequences of the selection error leading to the RAE should become more evident in the entire talent development system in this sport in order to get the chance to minimize the discrimination of relatively younger and late maturing athletes.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institutional Review Board of the Department of Sport Science of the University of Innsbruck. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

LS-M, CH, and CR collected the data. LS-M analyzed the data, prepared tables and figures, and wrote the manuscript. EM analyzed and interpreted the data. All authors designed the study, contributed to data interpretation and manuscript revision, and read and approved the submitted version.

ACKNOWLEDGMENTS

The authors want to thank all ski racers for their participation and the University of Innsbruck for the funding of the publication.

REFERENCES

Baker, J., Janning, C., Wong, H., Cobley, S., and Schorer, J. (2014). Variations in relative age effects in individual sports: skiing, figure skating and gymnastics. *Eur. J. Sport Sci.* 14, 183–190. doi: 10.1080/17461391.2012.671369

Barnsley, R. H., Thompson, A. H., and Barnsley, P. E. (1985). Hockey success and birthdate: the relative age effect. *Can. Assoc. Health Phys. Educ. Rec.* 51, 23–28.

Bjerke, Ø., Pedersen, A. V., Aune, T. K., and Lorås, H. (2016). An inverse relative age effect in male alpine skiers at the absolute top level. *Front. Psychol.* 8:1210. doi: 10.3389/fpsyg.2017.01210

Cobley, S., Baker, J., Wattie, N., and McKenna, J. (2009). Annual age-grouping and athlete development. A meta-analytical review of relative age effects in sports. *Sports Med.* 39, 235–256. doi: 10.2165/00007256-200939030-00005

Delorme, N., and Raspaud, M. (2009). The relative age effect in young French basketball players: a study on the whole population. *Scand. J. Med. Sci. Sports* 19, 235–242. doi: 10.1111/j.1600-0838.2008.00781.x.

Deprez, D., Coutts, A. J., Fransen, J., Deconinck, F., Lenoir, M., and Vaeyens, R. (2013). Relative age, biological maturation and anaerobic characteristics in elite youth soccer players. *Int. J. Sports Med.* 34, 897–903. doi: 10.1055/s-0032-1333262

Edgar, S., and O'Donoghue, P. (2005). Season of birth distribution of elite tennis players. *J. Sports Sci.* 23, 1013–1020. doi: 10.1080/02640410400021468

Gil, S. M., Badiola, A., Bidaurrazaga-Letona, I., Zabala-Lili, J., Gravina, L., Santos-Concejero, J., et al. (2014). Relationship between the relative age effect and anthropometry, maturity and performance in young soccer players. *J. Sports Sci.* 32, 479–486. doi: 10.1080/02640414.2013.832355

Helsen, W. F., Baker, J., Michiels, S., Schorer, J., Van Winckel, J., and Williams, A. M. (2012). The relative age effect in European professional soccer: did ten years of research make any difference? *J. Sports Sci.* 30, 1665–1671. doi: 10.1080/02640414.2012.721929

Helsen, W. F., van Winckel, J., and Williams, A. M. (2005). The relative age effect in youth soccer across Europe. *J. Sports Sci.* 23, 629–636. doi: 10.1080/02640410400021310

Hurley, W., Lior, D., and Tracze, S. (2001). A proposal to reduce the age discrimination in Canadian minor hockey. *Can. Public Policy* 27, 65–75. doi: 10.2307/3552374

Lames, M., Augste, C., Dreckmann, C., Görsdorf, K., and Schimanski, M. (2008). Der "Relative Age Effect" (RAE): neue Hausaufgaben für den Sport. *Leistungssport* 37, 4–9.

Lovell, R., Towlson, C., Parkin, G., Portas, M., Vaeyens, R., and Cobley, S. (2015). Soccer player characteristics in english lower-league development programmes: the relationships between relative age, maturation, anthropometry and physical fitness. *PLoS ONE* 10:e0137238. doi: 10.1371/journal.pone.0137238

Malina, R. M., Eisenmann, J. C., Cumming, S. P., Ribeiro, B., and Aroso, J. (2004). Maturity-associated variation in the growth and functional capacities of youth football (soccer) players 13-15 years. *Eur. J. Appl. Physiol.* 91, 555–562. doi: 10.1007/s00421-003-0995-z

Medic, N., Young, B. W., Starkes, J. L., Weir, P. L., and Grove, J. R. (2009). Gender, age and sport differences in relative age effects among US Masters swimming and track and field athletes. *J. Sports Sci.* 27, 1535–1544. doi: 10.1080/02640410903127630

Mirwald, R. L., Baxter-Jones, A. D., Bailey, D. A., and Beunen, G. P. (2002). An assessment of maturity from anthropometric measurements. *Med. Sci. Sports Exerc.* 34, 689–694. doi: 10.1097/00005768-200204000-00020

Müller, L., Gonaus, C., Perner, C., Müller, E., and Raschner, C. (2017a). Maturity status influences the relative age effect in national top level youth alpine ski racing and soccer. *PLoS ONE* 12:e0181810. doi: 10.1371/journal.pone.0181810

Müller, L., Hildebrandt, C., and Raschner, C. (2015a). The relative age effect and the influence on performance in youth alpine ski racing. *J. Sports Sci. Med.* 14, 16–22.

Müller, L., Hildebrandt, C., and Raschner, C. (2017b). The role of a relative age effect in the 7th International Children's Winter Games 2016 and the influence of the biological maturity status on selection. *J. Sports Sci. Med.* 16, 195–202.

Müller, L., Hildebrandt, C., Schnitzer, M., and Raschner, C. (2016a). The role of a relative age effect in the 12th Winter European Youth Olympic Festival in 2015. *Percept. Mot. Skills* 122, 701–718. doi: 10.1177/0031512516640390

Müller, L., Müller, E., Hildebrandt, C., Kornexl, E., and Raschner, C. (2015b). Influential factors on the relative age effect in alpine ski racing. *PLoS ONE* 10:e0134744. doi: 10.1371/journal.pone.0134744

Müller, L., Müller, E., Hildebrandt, C., and Raschner, C. (2016b). Biological maturity status strongly intensifies the relative age effect in alpine ski racing. *PLoS ONE* 11:e0160969. doi: 10.1371/journal.pone.0160969

Müller, L., Raschner, C., Kornexl, E., Hildebrandt, C., Bacik, M., Kröll, J., et al. (2012). Zum Relativen Alterseffekt im internationalen alpinen Skirennlauf. *Leistungssport* 42, 5–12.

Musch, J., and Grondin, S. (2001). Unequal competition as an impediment to personal development: a review of the relative age effect in sport. *Dev. Rev.* 21, 147–167. doi: 10.1006/drev.2000.0516

Nakata, H., and Sakamoto, K. (2012). Sex differences in relative age effects among Japanese athletes. *Percept. Mot. Skills* 115, 179–186. doi: 10.2466/10.05.17.PMS.115.4.179-186

Nakata, H., and Sakamoto, K. (2013). Relative age effects in Japanese baseball: an historical analysis. *Percept. Mot. Skills* 117, 276–289. doi: 10.2466/10.25.PMS.117x13z1

Nuttall, F. Q. (2015). Body mass index: obesity, bmi, and health: a critical review. *Nutr. Today* 50, 117–128. doi: 10.1097/NT.0000000000000092

Raschner, C., Müller, E., Schwameder, H., Haid, C., and Männel, D. (1995). "Zum Einfluss anthropometrischer Merkmale auf die Wettkampfleistung im Slalom bei jugendlichen Skirennläufern," in *Sportliche Leistung und Training,* eds J. Krug and H. Minow (Sankt Augustin: Academia), 341–346.

Raschner, C., Müller, L., and Hildebrandt, C. (2012). The role of a relative age effect in the first winter Youth Olympic Games in 2012. *Br. J. Sports Med*. 46, 1038–1043. doi: 10.1136/bjsports-2012-091535

Raschner, C., Müller, L., and Hildebrandt, C. (2015). "Talent detection and development in Alpine skiing," in *Science and Skiing VI*, eds E. Müller, J. Kröll, S. Lindinger, J. Pfusterschmied, and T. Stöggl (Maidenhead: Meyer and Meyer Sport), 65–75.

Romann, M., and Cobley, S. (2015). Relative age effects in athletic sprinting and corrective adjustments as a solution for their removal. *PLoS ONE* 10:e0122988. doi: 10.1371/journal.pone.0122988

Romann, M., and Fuchslocher, J. (2013). Relative age effects in Swiss junior soccer and their relationship with playing position. *Eur. J. Sport Sci.* 13, 356–363. doi: 10.1080/17461391.2011.635699

Romann, M., and Fuchslocher, J. (2014). Survival and success of the relatively oldest in swiss youth skiing competition. *Int. J. Sports Sci. Coach*. 9, 347–356. doi: 10.1260/1747-9541.9.2.347

Sherar, L. B., Baxter-Jones, A. D., Faulkner, R. A., and Russell, K. W. (2007). Do physical maturity and birth date predict talent in male youth ice hockey players? *J. Sports. Sci*. 25, 879–886. doi: 10.1080/02640410600908001

Steidl-Müller, L., Hildebrandt, C., Raschner, C., and Müller, E. (2019). Challenges of talent development in alpine ski racing: a narrative review. *J. Sports Sci.* 37, 601–612. doi: 10.1080/02640414.2018.1513355

Torres-Unda, J., Zarrazquin, I., Gil, J., Ruiz, F., Irazusta, A., Kortajarena, M., et al. (2013). Anthropometric, physiological and maturational characteristics in selected elite and non-elite male adolescent basketball players. *J. Sports Sci.* 31, 196–203. doi: 10.1080/02640414.2012.725133

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.

The handling editor declared a past supervisory role and past co-authorships with one of the authors EM.

frontiers in Sports and Active Living

ORIGINAL RESEARCH
published: 12 November 2019
doi: 10.3389/fspor.2019.00060

Analysis of a Biathlon Sprint Competition and Associated Laboratory Determinants of Performance

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OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Sports Science, Technology and Engineering, a section of the journal Frontiers in Sports and Active Living

Received: *11 August 2019*
Accepted: *24 October 2019*
Published: *12 November 2019*

Citation:
Luchsinger H, Talsnes RK, Kocbach J and Sandbakk Ø (2019) Analysis of a Biathlon Sprint Competition and Associated Laboratory Determinants of Performance. Front. Sports Act. Living 1:60. doi: 10.3389/fspor.2019.00060

Biathlon is an Olympic winter-sport where cross-country (XC) skiing in the skating technique is combined with rifle shooting. In the biathlon sprint competition for men, three laps of 3.3-km are interspersed with a 5-shot shooting sequence in the prone and standing position. Our purpose was to investigate the contribution from overall XC skiing performance, the performance in different terrain sections and shooting performance to the overall biathlon sprint race performance, as well as the relationship to laboratory-measured capacities obtained during treadmill roller ski skating. Eleven elite male biathletes were tracked by a Global Positioning System (GPS) device and a heart rate (HR) monitor during an international 10-km biathlon sprint competition. Within a period of 6 weeks prior to the competition, physiological responses, and performance during submaximal and maximal treadmill roller skiing were measured. Stepwise multiple regression analysis revealed that XC skiing time, shooting performance, shooting time and range time explained 84, 14, 1.8, and 0.2% of the overall sprint race performance (all $p < 0.01$). Time in uphill, varied, and downhill terrains were all significantly correlated to the total XC skiing time ($r = 0.95$, 0.82, 0.72, respectively, all $p < 0.05$). Percent of maximal HR (HRmax) and rating of perceived exertion (RPE) during submaximal roller skiing, and time-to-exhaustion during incremental roller skiing correlated significantly with overall biathlon sprint race performance and overall XC skiing time ($r = 0.64$–0.95, all $p < 0.05$). In conclusion, XC skiing performance provided greatest impact on biathlon sprint performance, with most of the variance determined by XC skiing performance in the uphill terrain sections. Furthermore, the ability to roller ski with a low RPE and %HRmax during submaximal speeds, as well as time-to-exhaustion during incremental roller skiing significantly predicted biathlon performance. Such laboratory-derived measures may therefore be validly used to distinguish biathletes of different performance levels and to track progress of their XC skiing capacity.

Keywords: biathletes, cross-country skiing, gross efficiency, maximal oxygen uptake, rifle shooting

INTRODUCTION

Biathlon is an Olympic winter-sport with two main components; cross-country (XC) skiing in the skating technique combined with 5-shot rifle shooting sequences. For men, the biathlon sprint competition consists of three laps of 3.3 km interspersed with shooting in the prone and standing position, in which each missed shot is penalized by adding a 150-m XC skiing loop (IBU, 2017). Shooting is performed on a 50 m shooting range using 0.22 caliber long rifles weighing >3.5 kg that the athletes carry on their back while skiing, and the circular hit areas are 45 mm in diameter in prone and 115 mm in standing shooting. Thus, success in biathlon demands high aerobic endurance capacity, an efficient skiing technique, as well as rapid and accurate shooting performed directly after high-intensity exercise.

A recent investigation of World Cup performance in biathlon sprint events shows that XC skiing time is the most distinguishing factor for the overall performance (Luchsinger et al., 2018), explaining ∼59–65% of the overall performance difference between top-10 results and those finishing among 21–30 in both sexes. Furthermore, ∼31–35% of the group-difference was explained by shooting performance (i.e., time spent in the penalty loop due to missed targets), whereas shooting time and range time (i.e., time at the shooting range minus shooting time) together explained only 4–6% of the group-difference in overall biathlon sprint performance. This is supported by the work of Skattebo and Losnegard (2017) where the largest between-athlete variability was found for XC skiing time followed by shooting performance during biathlon sprint races.

Although the scientific understanding of XC skiing demands is relatively well-defined (Sandbakk and Holmberg, 2014, 2017; Losnegard, 2019), a more comprehensive understanding of the demands of XC skiing performance in biathlon is needed. In their review of the scientific literature in biathlon, Laaksonen et al. (2018a) wrote that the forced breaks (when shooting) between bouts of close to maximal intensity skiing is unique in endurance sports. More accurate analyses of the skiing component of biathlon races can be gained by combining wearable Global Positioning Systems (GPS) with heart rate (HR) monitoring during competitions. However, while this methodology has not yet been employed in biathlon events for scientific purposes, the many GPS-based studies performed in XC skiing have revealed that more than 50% of the total race time is spent uphill and that these terrain sections are most performance-differentiating (Andersson et al., 2010; Bolger et al., 2015; Sandbakk et al., 2016b; Solli et al., 2018). Although the physiological demands of the XC skiing component of biathlon competitions are comparable to those seen in XC skiing, biathletes compete only in the skating technique and with a rifle carried on the back that alters the energy cost and kinematical aspects of skiing (Stöggl et al., 2015). In addition, biathletes' pacing strategies need to take into account the important 25–30 s shooting sequences during the competition (Laaksonen et al., 2018b). Therefore, biathletes may use less effort on uphill terrain sections to avoid accumulation of fatigue when approaching the shooting range.

In addition, knowledge about the underlying laboratory-measured performance-determinants for XC skiing performance in modern biathlon sprint races are lacking. XC skiing performance has previously been linked to peak oxygen uptake (VO_{2peak}) and the ability to effectively convert metabolic energy into external work rate and speed [i.e., gross efficiency (GE)] in XC skiers (Sandbakk et al., 2010, 2011b, 2013, 2016a,b) and Nordic combined athletes (Sandbakk et al., 2016c; Rasdal et al., 2017). This has provided coaches and athletes with valuable insight into the relationships between competition performance and different performance-indices obtained in the laboratory. However, the current knowledge on the importance of these factors in biathlon is scarce, and their association to performance has not been studied since the mid-1990s (Rundell, 1995; Rundell and Bacharach, 1995).

On this basis, the present study aims to investigate the contribution from overall XC skiing performance, performance in different terrain sections, and shooting performance to the overall biathlon sprint race performance. In addition, we aim to examine the relationships between overall biathlon and XC skiing performance to laboratory-measured capacities obtained during treadmill roller skiing. We hypothesize that XC skiing performance on uphill terrain provides the strongest relationships with overall biathlon sprint performance, and that uphill performance would correlate strongly with VO_{2peak} and gross efficiency while treadmill roller skiing.

TABLE 1 | Characteristics (mean ± SD) of the eleven elite male biathletes participating in the study.

Age (yrs)	21.4 ± 2.1
Body height (cm)	181.1 ± 4.7
Body mass (kg)	76.5 ± 4.8
Body mass index ($kg \cdot m^{-2}$)	23.5 ± 1.3
Rifle weight (kg)	4.0 ± 0.3
Annual training[a] (hrs)	685 ± 115
Physical training[a] (hrs)	585 ± 87
Shooting training[a] (hrs)	100 ± 34
Maximum HR[b] ($beats \cdot min^{-1}$)	198 ± 8

[a] *Training volume categorized into hours of total training, physical training and shooting training during the last 12 months prior to the competition.*
[b] *Self-reported maximum heart rate (HR_{max}) based on outdoor tests from the year prior to this study.*

METHODS

Participants

Eleven elite male biathletes, members of the junior and recruitment team of the Norwegian Biathlon Association, competing in the IBU-cup, Jr. World championships and at the highest level in the Norwegian cup, volunteered to participate in the study. The participant's age, anthropometrics and training characteristics are presented in **Table 1**.

Ethics Statement

The Regional Committee for Medical and Health Research Ethics waives the requirement for ethical approval for this study. Therefore, the ethics of the study is done according to the institutional requirements and approval for data security and handling was obtained from the Norwegian Centre for Research Data. Prior to the data collection, all participants provided written informed consent to voluntarily take part in the study. The participants were informed that they could withdraw from the study at any point in time without providing a reason for doing so.

Overall Design

During an international 10-km biathlon sprint competition in mid-November 2016, regulated by the International Biathlon Association (IBU), all study participants were tracked by a GPS device and HR monitor. The racecourse was mapped with a coupled GPS and barometer to provide a valid course and elevation profile. The XC skiing course was further divided into uphill, varied, and downhill terrain sections, and the overall shooting component was separated into range time (time spent at the shooting range excluding shooting time), shooting time and penalty time (time spent in the penalty loop as a consequence of misses at the shooting range). Within a period of 6 weeks prior to the competition, all participants completed submaximal and maximal laboratory testing while roller skiing on a treadmill using different speed and incline combinations.

Laboratory Testing

Initially, the participants performed 15 min of low-intensity warm-up while roller skiing on the treadmill. The first 10 min of the warm-up were conducted without the rifle and the last 5 min while carrying the rifle on their back. Thereafter, the submaximal tests were performed consisting of two 5-min stages (one with and one without carrying the rifle) with 2-min recovery in-between using each of the three most important sub-techniques (G2–G4) in the skating technique (for a more detailed description of sub-techniques, see Andersson et al., 2010). The first two stages were conducted utilizing the G4 sub-technique at 3% inclination and 20 $km \cdot h^{-1}$, followed by two stages using the G3 sub-technique at 5% inclination and 15 $km \cdot h^{-1}$. The two last stages were performed with the G2 sub-technique at 12% inclination and a speed of 8 $km \cdot h^{-1}$, respectively. The inclines were based on previous research indicating which inclines the different sub-techniques are naturally employed. The speeds were chosen to match all inclines for metabolic cost, based on pilot tests of biathletes and XC skiers in our laboratory. Respiratory variables and HR were measured continuously and the average of the last 2 min of each stage was used for steady-state analyses. Blood lactate concentrations and RPE were determined directly after completing each submaximal stage. In the final analyses, only the measurements using the rifle were used. After a 5-min recovery period, all participants completed maximal roller skiing using an incremental test to exhaustion to determine VO_{2peak} and time to exhaustion (TTE; as a measure of performance). The starting incline and speed was 10% and 11 $km \cdot h^{-1}$. The initial speed was kept constant, while the incline was increased by 2%-points every minute up to 14%. Thereafter, the speed was increased by 1 $km \cdot h^{-1}$ every minute until exhaustion. Respiratory variables and HR were measured continuously and VO_{2peak} was defined as the average of the three highest and consecutive 10 s measurements. Peak HR (HR_{peak}) was defined as the highest 5 s HR measurement during the test. Blood lactate concentrations and RPE were measured directly after the maximal-test. Treadmill roller skiing was performed on a 5 × 3 m motor-driven treadmill (Forcelink B.V., Culemborg, The Netherlands) with non-slip rubber surface on the treadmill belt, allowing the participants to use their own poles with special carbide tips. To minimize variations in roller resistance, the participants used the same pair of skating roller skis with standard category 2 wheels (IDT Sports, Lena, Norway). Before the tests, rolling friction force (F_f) was tested with a towing test as previously described (Sandbakk et al., 2010). The rolling friction coefficient (μ) was determined by dividing F_f by the normal force ($F_n = F_f / F_n$), and provided an average μ value of 0.0195, which was included in the calculation of work rate. The biathletes used their own rifle with an average weight of 4.0 ± 0.3 kg during laboratory testing.

Respiratory variables were measured using open-circuit indirect calorimetry with mixing chamber and 30 s averages of the respiratory variables were used (Oxycon Pro, Jaeger GmbH, Hoechberg, Germany). The instruments were calibrated against ambient air conditions and certified gases of known concentrations of O_2 (15.0%) and CO_2 (5.0%) before each test session. The flow transducer (Triple V, Erick Jaeger GmbH, Hoechberg, Germany) was calibrated using a 3-L high-precision calibration syringe (Calibration syringe D, SensorMedics, Yorba Linda, CA, USA). HR was continuously measured with a Polar V800 monitor and synchronized with the Oxycon Pro system. Blood lactate in 20 μL of blood was taken from the fingertip and measured using the stationary Biosen C-Line lactate analyzer (Biosen, EKF Industrial Electronics, Magdeburg, Germany). The device was calibrated every 60 min with a 12 $mmol \cdot L^{-1}$ standard concentration. Rating of perceived exertion (RPE) was determined using the 6–20 Borg Scale (Borg, 1982). The participants' body-mass and mass of the rifle were measured using a precise weight (Seca, model 708, GmbH, Hamburg, Germany), and body-height using a calibrated stadiometer (Holtain Ltd, Crosswell, UK), prior to the test.

Work rate was calculated as the sum of power against gravity and friction: $P_g + P_f = mgv\,[\sin(\alpha) + \cos(\alpha)\mu]$, with P_g being power against gravity, P_f power against friction, m the biathletes body-mass including skiing shoes, roller skis (and the rifle when roller skiing with the rifle), g the gravitational constant, α the treadmill incline, μ the frictional coefficient and v the treadmill speed. The aerobic metabolic rate was calculated as the product of VO_2 and the oxygen energetic equivalent using the associated respiratory exchange ratio and standard conversion tables (Peronnet and Massicotte, 1991). GE was defined as the ratio of work rate and aerobic metabolic rate and calculated from the submaximal tests (Sandbakk et al., 2010).

Competition Analysis

Prior to the competition, all the participants completed low-intensity warm-up procedures according to their own optimized protocols used in both training and competition. All participants used their own equipment during the competition, including rifle (4.0 ± 0.3 kg), poles (91 ± 1% of body height), skating XC skiing shoes, and skating XC skis. The

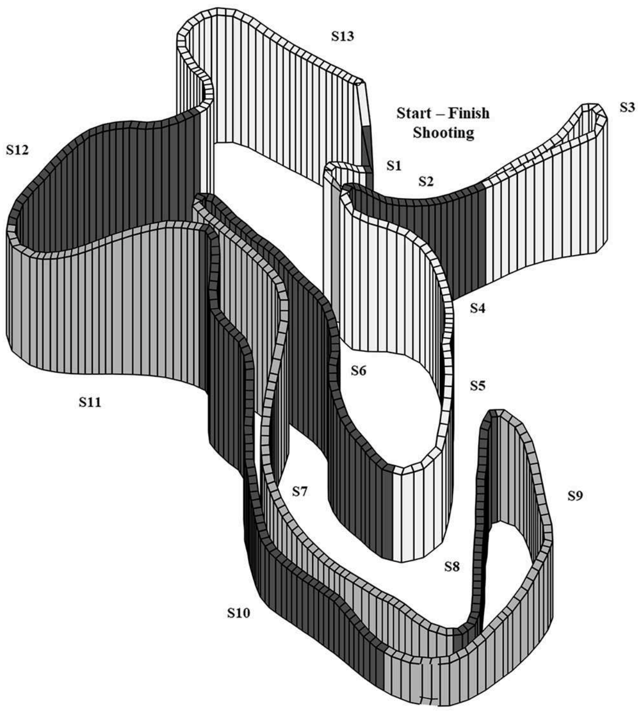

FIGURE 1 | 3D illustration of the 3015 m XC skiing racecourse divided into 13 different terrain sections. Detailed information about the terrain sections is described in **Table 3**.

skis were accustomed to individual preferences and prepared for the current conditions with appropriate ski base material and chamber stiffness. The weather conditions were stable throughout the entire competition with average ambient air and snow temperatures of −5.5 and −7.5°C, respectively. The average relative humidity was 85% during the competition and the wind was low and stable at the shooting range, varying between 0.3 and 1.0 m/s. Weather conditions were continuously registered during the competition using a weather station developed by the Norwegian Top Sport Centre (delivered by Airtight Ltd., Oslo, Norway), measuring both air and snow temperatures and humidity. Wind speeds during the competition were collected from the official shooting results (Biathlon, 2017). The racecourse consisted of a combination of artificial and natural snow and was machine-groomed the same morning as the competition day. The course was set in an open area with minimal tree cover and no steep mountains that could interfere with the GPS signals. Course and elevation profiles of the racecourse were measured with an integrated GPS and barometry using a Garmin Forerunner 920 XT (Garmin Ltd., Olathe, Kansas, USA), which collected position and altitude data at a 1 Hz sampling rate to define a reference course with accompanying altitude profile as previously described by Bolger et al. (2015) and Sandbakk et al. (2016b). The participants hit rate (number of targets hit) was provided by the official competition shooting results collected with an electronic target system (Megalink) (Biathlon, 2017). Penalty time was used as the measure of shooting performance in multiple regression and correlation analyses. The XC skiing course was divided into uphill, varied, and downhill terrain that equaled 37, 29, and 34% of the total course distance, respectively. A part of the XC skiing course prior to the shooting range was defined for analysis of pacing toward shooting. This part of the course included terrain section 12, defined as uphill, and section 13, defined as varied terrain (**Figure 1**, **Table 3**). In addition, each participant's time spent in this part toward shooting was divided by the total XC skiing time in uphill and varied sections on each lap for analyses of their relative time in this "preparation phase prior to shooting" compared to the rest of the course. The classification of different terrain sections was based on the International Ski Federation (FIS) homologation manual for XC skiing racecourses (FIS, 2017). A section boundary was defined where a change between positive and negative gradient in the XC skiing course profile occurred. Terrain sections with climb >10 m and gradient >6% were classified as uphill sections. Sections with descent >10 m and negative gradient >6% were classified as downhill sections. Remaining sections were classified as varied terrain, including short uphill and downhill sections interspersed with flat sections. A part of the racecourse, consisting of flat terrain in the start and finish of the competition, was not included in the final analysis to ensure that the start and final sprint would not affect the analyses of pacing strategies. The exact distance for each lap of the XC skiing racecourse was then 3,015 m.

During the competition, each participant was tracked by a Polar V800 GPS (Polar Electro Oy, Kempele, Finland), which collected position and HR data at a 1 Hz sampling rate. All GPS watches were turned on at least 30 min before the start of the race to ensure that the GPS watches could acquire contact with as many satellites as possible before race start, in order to optimize GPS accuracy for the duration of the race. Furthermore, data for all the participants were adapted to the reference course by fitting each competitors' GPS track to points along the reference course. This method, developed in cooperation between the national biathlon and XC ski federations, Norwegian Olympic Sports Centre and academic institutions provide sufficiently accurate data for the analyses needed here, amounting to a measurement error of up to ±1 s for each 180 m-split, when being compared to more accurate GPS-systems (Gløersen et al., 2018). Virtual split times were defined at every section boundary (uphill, downhill, varied terrain) along the course. Virtual split times in the shooting component were defined using a combination of GPS position and speed data. The time each participant spent in the different components of the race, as well as HR characteristics were calculated based on these virtual split times. Shooting time was defined as the time on the shooting range when speed was below 1.8 m/s (when athletes were at the shooting mat), whereas penalty time was defined as the time spent between a point after the range (i.e., before the penalty loop) and a point after the penalty loop. Thus, athletes with no mistakes also had a short penalty time. Range time was defined as the time spent at the shooting range, without shooting time.

Statistical Analysis

All data were tested for normality using a Shapiro–Wilk test in combination with visual inspection of data, and all variables are presented as mean ± SD. Correlations between overall biathlon sprint race performance and the different sections of the race, as well as correlations to laboratory capacities, were calculated using the Pearson's product-moment correlation coefficient or with the non-parametric Spearman's rank in cases where data were not normally distributed. Deviation from normally distributed data only occurred in the case of blood lactate concentration during submaximal testing of the three sub-techniques. In these cases, the Spearman's rank test was applied. The coefficient of variation (CV = standard deviation/mean) of time in different terrain sections of the XC skiing racecourse was calculated. Differences between prone and standing position with respect to shooting time and HR, as well as differences in pacing between laps, were tested using the paired sample *t*-test procedure. In addition, we performed two different stepwise multiple regression analyses, with model 1 having overall biathlon performance as dependent variable and XC skiing performance, shooting performance, shooting time, and range time as independent variables. In model 2, XC skiing performance was the dependent variable, and time in different terrains were independent variables. Alpha values of <0.05 determined the level of statistical significance and alpha values between 0.05 and 0.1 were considered trends. All statistical analyses were performed using IBM SPSS Software for Mac, Version 21.0 (SPSS Inc., Chicago, IL).

TABLE 2 | Overall performance, shooting performance, and time spent in the different components of a biathlon sprint competition among eleven elite male biathletes (mean ± SD).

Overall time (s)	1,574 ± 52		
XC skiing time (s)	1,355 ± 43		
Overall shooting component (s)	219 ± 23		
Terrain sections (s)	**Uphill**	**Varied**	**Downhill**
	701 ± 31	339 ± 11	315 ± 6
Shooting performance	**Prone**	**Standing**	**Total**
Hit rate (%)	91 ± 7	86 ± 6	89 ± 9
Penalty time (s)	34 ± 15	44 ± 15	78 ± 21
Shooting time (s)	31 ± 5	27 ± 4	58 ± 8
Range time (s)	41 ± 1	42 ± 1	83 ± 2

RESULTS

Overall Biathlon Sprint Race Performance

The distribution of XC skiing time, penalty time, shooting time, and range time in the overall biathlon sprint race time was 86.0, 5.0, 4.0, and 5.0%, respectively (**Table 2**). Stepwise multiple regression analysis demonstrated that XC skiing time explained

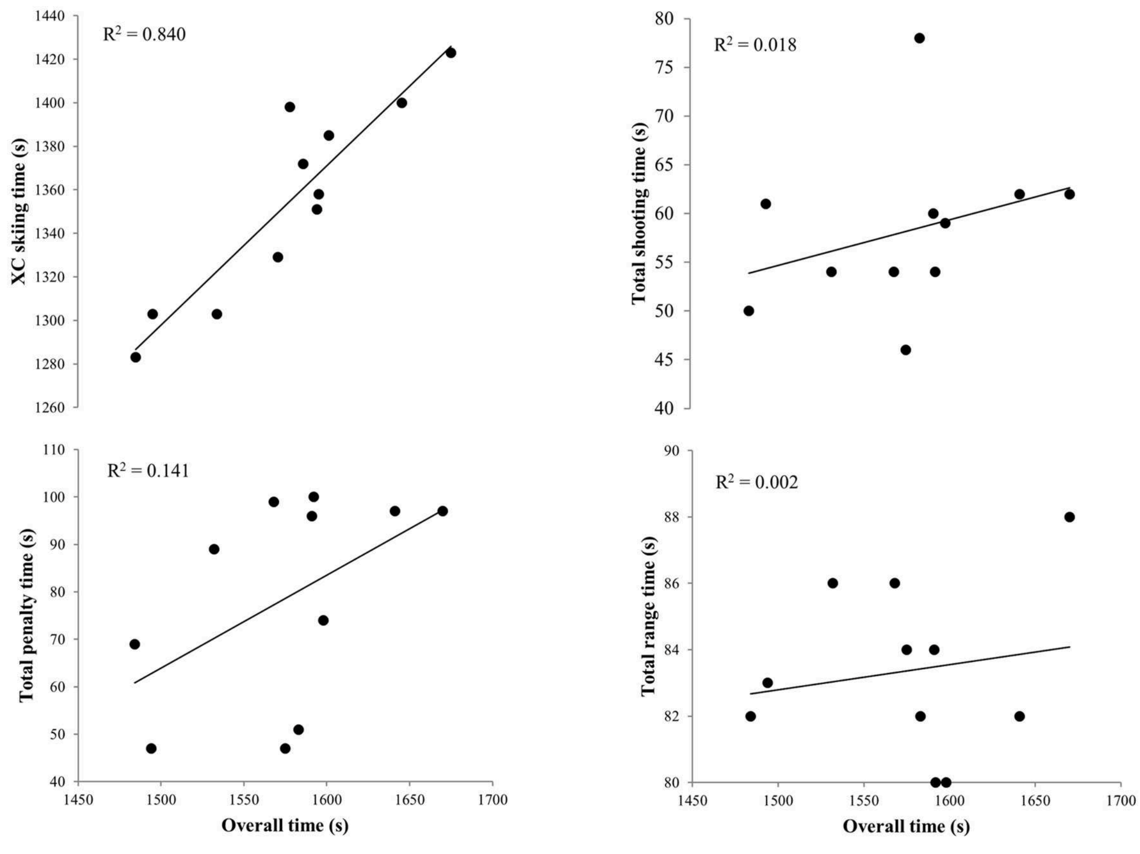

FIGURE 2 | Overall competition time in relationship to XC skiing time, penalty time, shooting time, and range time during a biathlon sprint competition among 11 elite male biathletes. Presented with individual data points and trend lines based on linear regression.

84.0% (semi-partial $R^2 = 0.603$), penalty time 14.2% (semi-partial $R^2 = 0.139$), shooting time 1.8% (semi-partial $R^2 = 0.020$), and range time 0.2% (semi-partial $R^2 = 0.002$) of overall sprint race time variance (all $p < 0.01$). In addition, XC skiing time was significantly correlated to overall biathlon sprint race performance ($r = 0.92$, $p < 0.01$; **Figure 2**).

XC Skiing Performance

Time, CVs of time and speed in different terrain sections of the XC skiing course are presented in **Table 3**. The distribution of total XC skiing time spent in uphill, varied, and downhill terrains were 52.0, 25.0, and 23.0%, respectively. Stepwise multiple regression analysis demonstrated that time in uphill explained 90.7% (semi-partial $R^2 = 0.315$), varied 8.6% (semi-partial $R^2 = 0.023$) and downhill terrain 0.7% (semi-partial $R^2 = 0.007$) of the total variation in overall XC skiing time (all $p < 0.01$). Time in uphill, varied, and downhill terrains were all significantly correlated to the overall XC skiing time ($r = 0.95$, 0.82, 0.72, respectively, all $p < 0.05$), and highest CVs of time were found in uphill terrain sections.

Shooting Performance

The average hit rate was 89 ± 9% with 91 ± 7% in the prone position, which was significantly better than the 86 ± 6% in the standing position ($p < 0.05$). On average, $\%HR_{max}$ was 87 ± 3% at the start of the shooting, both in the prone and standing position. During shooting, HR_{max} decreased to 69 ± 6% in the prone position, whereas this drop was significantly smaller, decreasing to 79 ± 4%, in the standing position (all $p< 0.01$). On average, the biathletes in this study shot 4 s (13%) faster in the standing than in prone position ($p < 0.05$). There was no significant relationship observed between the biathletes $\%HR_{max}$ at the start of shooting and shooting performance, in either prone or standing shooting.

Pacing Strategies and Skiing Speed Toward Shooting

Speed and HR profiles for the three laps are shown in **Figures 3**, **4**. Lap times (details provided in **Table 3**) on all three laps were significantly correlated to the overall XC skiing performance ($r = 0.84$, 0.95, 0.85, $p < 0.01$). The second and third laps were skied with 4.4 and 2.9% slower speeds in comparison to the first lap, respectively, with the last lap being significantly faster than the second lap (all $p < 0.05$). The participant's mean time in the defined section prior to shooting was 71 ± 2 and 73 ± 2 s for the prone and standing position, respectively. However, relative times in this section compared to total time in uphill and varied sections in the rest of the course on each lap were 0.7 ± 0.9%—points faster on the second and 3.1 ± 2.0%—points faster on the third lap compared to the first lap ($p < 0.05$). In addition, relative time in the section prior to shooting was inversely correlated to total time on lap 2 ($r = -0.64$, $p < 0.05$) and lap 3 ($r = -0.75$, $p < 0.01$) but not on lap 1 ($r = -0.49$, $p = 0.13$). There was no significant correlation observed between absolute or relative time or intensity in the last section before shooting and shooting performance (i.e., penalty time) in the prone or the standing position.

Laboratory Determinants of XC Skiing Performance

Results from laboratory testing is provided in **Table 4**. During submaximal roller skiing, RPE and $\%HR_{max}$ for G2 and G3 sub-techniques were significantly correlated (**Figure 5**, all $p < 0.05$), and tended to correlate for the G4 technique (both RPE and $\%HR_{max}$ $0.06 < p < 0.07$) with overall biathlon sprint race performance, XC skiing time and time spent in all terrains (**Table 5**). Furthermore, blood lactate concentrations in the G3 and G2 sub-techniques were significantly correlated to overall XC skiing time and time spent in downhill terrain sections (all $p < 0.05$) and showed a trend to time spent in uphill terrain ($p = 0.07$ and $p = 0.10$ for G2 and G3, respectively).

The observed correlations between submaximal roller skiing and XC skiing performance did not change when using measurements from roller skiing without the rifle, although carrying a rifle was associated with a 5% higher submaximal oxygen cost, 3% higher HR, ∼0.5 mmol/L higher blood lactate concentrations and 7% higher ratings of perceived exertion in comparison to skiing without a rifle (all $p < 0.01$). GE was unchanged, and the observed differences in GE between skiing with and without rifle were independent of sub-technique utilized at the different speeds and inclines (see details in **Table 4**).

TTE during maximal roller skiing correlated significantly with overall biathlon sprint race time, XC skiing time, as well as time spent in varied and downhill terrain (**Table 5**; all $p < 0.05$), whereas TTE tended to correlate with time in uphill terrain ($p = 0.07$). In addition, TTE did not correlate with XC skiing performance on the first or second lap but correlated strongly with the 3rd lap ($r = -0.84$, $p < 0.01$).

DISCUSSION

The primary aim of the present study was to investigate the contribution from XC skiing and shooting performance to the overall biathlon sprint performance, as well as the relationship to laboratory-measured capacities obtained during treadmill roller skiing. The main findings from the stepwise multiple regression analyses showed that XC skiing time explained 84% of the overall biathlon sprint performance, with shooting performance (i.e., penalty time) explaining 14% of the remaining variance and shooting time and range time together explaining the remaining 2%. Time spent in uphill terrain sections had the strongest impact on XC skiing performance (and explained 91% of the variance), although performance in all types of terrain showed significant associations. In addition, RPE and $\%HR_{max}$ during submaximal roller skiing as well as TTE during incremental treadmill roller skiing in the laboratory were significantly correlated to overall biathlon performance and isolated XC skiing performance.

Overall Biathlon Sprint Race Performance

In the current study, XC skiing performance was clearly the most important contributor to the overall biathlon sprint performance, which support previous studies on biathlon sprint races (Skattebo and Losnegard, 2017; Luchsinger et al., 2018). In our approach,

TABLE 3 | Length (for each 3-km lap), elevation, time and speed, as well as coefficient of variance (CV) of time within different sections of terrain during the three laps of the sprint competition among eleven elite male biathletes.

				Lap 1			Lap 2			Lap 3		
Section number	**Terrain type**	**Section length (m)**	**Elevation (m/%)**	**Mean section time (s)**	**Time CV (%)**	**Mean section speed (m/s)**	**Mean section time (s)**	**Time CV (%)**	**Mean section speed (m/s)**	**Mean section time (s)**	**Time CV (%)**	**Mean section speed (m/s)**
S1	Varied[a]	45	–	9 ± 1	5.3	4.8	13 ± 2	13.6	3.4	13 ± 2	12.8	3.5
S2	Downhill	128	14/11	14 ± 1	6.2	9.5	14 ± 1	5.6	9.2	15 ± 1	7.3	8.9
S3	Varied[a]	226	–	27 ± 1	3.3	8.3	29 ± 1	4.4	7.8	30 ± 1	4.4	7.7
S4	Uphill	125	11/9	22 ± 1	5.2	5.6	24 ± 1	4.6	5.2	23 ± 2	6.7	5.4
S5	Varied[a]	304	–	36 ± 2	4.4	8.4	38 ± 2	4.5	8.0	38 ± 2	6.0	8.1
S6	Uphill	279	18/7	55 ± 3	5.3	5.0	58 ± 3	5.6	4.8	57 ± 4	6.9	4.9
S7	Downhill	428	27/6	41 ± 1	3.1	10.4	42 ± 1	2.8	10.2	43 ± 1	3.0	10.0
S8	Uphill	183	14/7	32 ± 2	5.8	5.8	33 ± 3	7.5	5.5	33 ± 2	6.6	5.6
S9	Downhill	288	18/6	30 ± 1	4.2	9.6	30 ± 1	3.4	9.6	31 ± 1	4.0	9.4
S10	Uphill	363	31/9	85 ± 6	6.6	4.2	87 ± 6	6.7	4.2	84 ± 7	8.1	4.3
S11	Downhill	178	15/8	19 ± 1	2.8	9.6	19 ± 1	3.4	9.4	19 ± 1	4.0	9.4
S12	Uphill	179	14/18	36 ± 1	4.0	5.0	37 ± 1	4.2	4.9	34 ± 2	7.1	5.2
S13	Varied[a]	289	–	35 ± 1	1.8	8.3	36 ± 1	2.4	8.1	35 ± 1	3.4	8.3
Sum	Varied	864	–	107	3.7	7.5	116	6.2	6.8	116	6.7	6.9
Sum	Uphill	1,129	88	230	5.4	5.1	239	5.7	4.9	231	7.1	5.1
Sum	Downhill	1,022	74	104	4.1	9.8	105	3.8	9.6	108	4.6	9.4
Total		3,015	118[b]	441 ± 14	3.2	6.8	460 ± 16	3.5	6.5	454 ± 20	4.4	6.6

[a]*Elevation is not provided for varied terrain sections since these parts of the course consist of small uphills and downhills, as well as flat sections. For detailed specifications of varied terrain, see the Methods section and* ***Figure 1****.*
[b]*Total climb in one lap.*

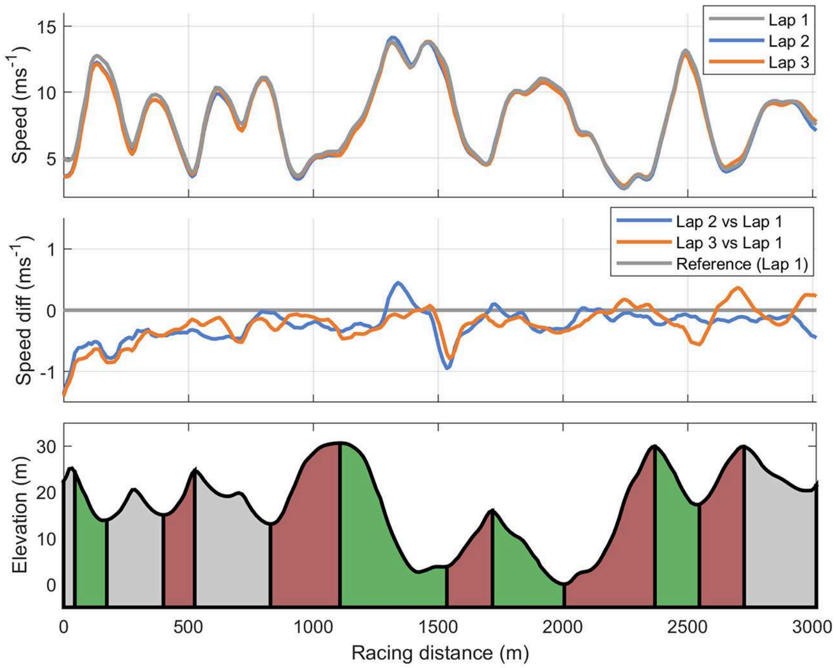

FIGURE 3 | Cross-country skiing speed for each of the three 3-km laps **(upper panel)** and speed differences on lap 2 and 3 compared to the first lap **(mid panel)** during a biathlon sprint competition among 11 elite male biathletes.

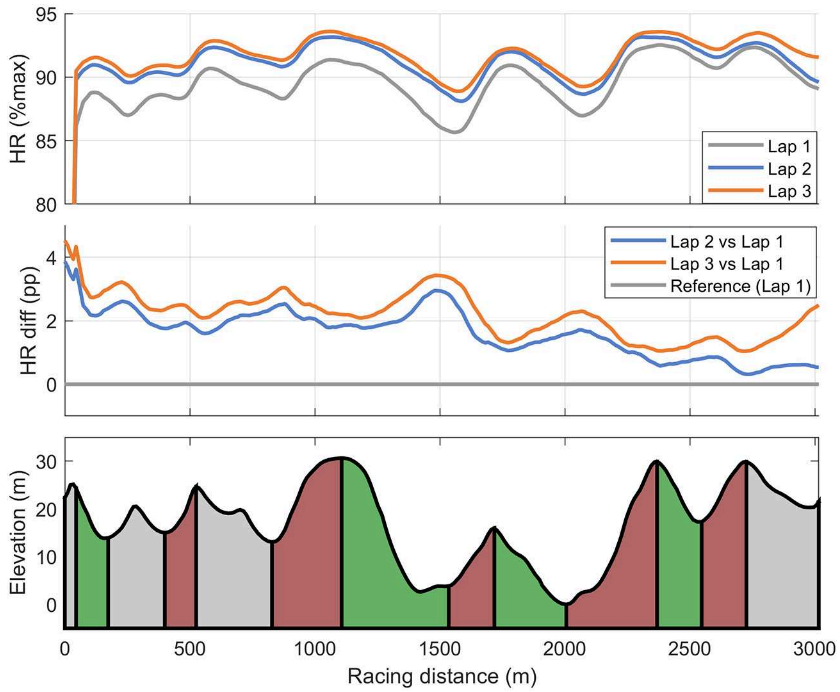

FIGURE 4 | Cross-country skiing heart rate (%HR_{max}) for each of the three 3-km laps **(upper panel)** and heart rate differences [in percent points (pp)] on lap 2 and 3 compared to first lap **(mid panel)** during a biathlon sprint competition among 11 elite male biathletes.

the stepwise multiple regression analysis demonstrated that XC skiing performance explained 84% of the variation in overall performance, while only 16% of the remaining variation in performance was explained by the overall shooting component (including shooting performance, shooting time, and range time). Furthermore, the correlation between XC skiing and overall performance was clearly larger than the corresponding correlations for the overall shooting component. These main findings extend upon the recent findings by Luchsinger et al. (2018) who revealed XC skiing time to be the most important contributor to the overall performance difference between top-10 results and those finishing among 21–30 in both sexes in biathlon World Cup sprint races. In the study by Luchsinger et al. (2018), XC time explained ∼60% of the variance in overall performance when averaged over 47 World Cup sprint races. The larger influence of XC skiing time found here may be due to different methodologies between the studies, as well as natural variations across competitions (e.g., racecourses with different terrain in the sections prior to shooting and variation in snow and weather conditions). In our case, the shooting conditions were good (i.e., low wind speeds and good visibility) and athletes had relatively high hit rates, similar to the 92–93% hit rates reported among top-10 racers in World Cup sprint races (Luchsinger et al., 2018). Thus, these factors could additionally have contributed to the high impact of XC skiing performance on the overall biathlon sprint performance in the current study. However, the previous studies also highlight the larger importance of XC skiing performance than shooting performance to the overall biathlon sprint performance. Extending upon these findings, the current study provides detailed insight into the different components of the biathlon sprint competition, such as the importance of XC skiing in different terrains and the effects of pacing strategy.

XC Skiing Performance

The relative distribution of time spent in the uphill terrain sections accounted for 52% of the total XC skiing time and, additionally, time spent uphill revealed a near perfect correlation with XC skiing time. These findings are supported by higher CVs of time within the uphill compared to varied and downhill terrain sections, indicating greatest variation in time spent uphill, followed by time spent in the varied and downhill terrain sections, respectively. Altogether, the stepwise multiple regression analysis demonstrated that time in uphill explained ∼91% of the variation in XC skiing performance. Indeed, uphill terrain as the most performance-differentiating part of the XC skiing performance is supported by previous research in XC skiing (Andersson et al., 2010; Bolger et al., 2015; Sandbakk et al., 2016b; Solli et al., 2018). However, in line with findings from XC skiing (Sandbakk et al., 2016b), performance in all types of terrain are important for achieving an excellent XC skiing performance in biathlon as shown by the significant correlations between all types of terrain and isolated skiing performance in this biathlon sprint race.

In line with findings from Biathlon World Cup sprint races (Luchsinger et al., 2018), the biathletes reduced their speed during the second and third lap compared to the first lap of the race, but skied the third lap faster compared to the second lap. This indicates that athletes maintain physical reserves to

TABLE 4 | Submaximal and maximal physiological responses and treadmill performance (mean ± SD) while roller skiing using different sub-techniques with (R) and without (N) the rifle on the back among eleven elite male biathletes.

Submaximal tests	**G4R**	**G4N**	**G3R**	**G3N**	**G2R**	**G2N**
VO_2 ($L \cdot min^{-1}$)	4.45 ± 0.28	4.24 ± 0.28**	4.44 ± 0.24	4.20 ± 0.23**	4.40 ± 0.26	4.20 ± 0.24**
VO_2 ($mL \cdot min^{-1} \cdot kg^{-1}$)	57.9 ± 2.8	55.3 ± 2.6**	57.7 ± 2.0	54.6 ± 1.8**	57.3 ± 2.4	54.6 ± 2.4**
VO_2 in % VO_{2peak}	79 ± 5	75 ± 4**	78 ± 4	74 ± 4**	78 ± 4	74 ± 4**
RER	0.95 ± 0.02	0.94 ± 0.03	0.94 ± 0.03	0.93 ± 0.03*	0.93 ± 0.03	0.91 ± 0.03**
HR ($beats \cdot min^{-1}$)	176 ± 8	171 ± 7**	178 ± 8	174 ± 8**	178 ± 7	174 ± 7**
HR in %HR_{max}	89 ± 3	87 ± 2**	90 ± 3	88 ± 3**	90 ± 3	88 ± 3**
RPE (6–20)	14 ± 1	13 ± 1**	14 ± 1	13 ± 1**	15 ± 1	14 ± 1**
BLa ($mmol \cdot L^{-1}$)	3.8 ± 1.3	3.3 ± 1.0**	4.3 ± 1.9	3.7 ± 1.7**	4.3 ± 2.0	4.0 ± 1.8**
GE (%)	14.6 ± 0.7	14.6 ± 0.8	15.4 ± 0.5	15.6 ± 0.6	16.7 ± 0.7	16.7 ± 0.7
VO_{2peak}-test						
VO_{2peak} ($L \cdot min^{-1}$)				5.63 ± 0.41		
VO_{2peak} ($mL \cdot min^{-1} \cdot kg^{-1}$)				73.7 ± 3.9		
Peak RER				1.12 ± 0.30		
Peak HR ($beats \cdot min^{-1}$)				193 ± 8		
Peak BLa ($mmol \cdot L^{-1}$)				13.5 ± 1.3		
RPE (6-20)				19 ± 1		
TTE (s)				260 ± 20		

*VO_2, oxygen uptake; HR, heart rate; HR_{max}, maximal heart rate based on outdoor tests from the year prior to this study; RPE, rating of perceived exertion; BLa, blood lactate concentration; GE, gross efficiency; VO_{2peak}, peak oxygen uptake from incremental test to exhaustion; TTE, time to exhaustion; *Significant difference between with and without rifle within sub technique (**$p < 0.01$,*$p < 0.05$).*

increase speed during the latter part of the race. Specifically, the slightly reduced speed during the second lap prior to shooting in the standing position may be a strategy to minimize a possible negative effect of exercise intensity on shooting performance. This assumption is strengthened by findings in XC skiing where the athletes (who do not stop to shoot during the race) employ a more clear positive pacing strategy (although with a short end spurt) (Bolger et al., 2015; Losnegard et al., 2016; Sandbakk et al., 2016b). Extending upon the findings from World Cup sprint races, the detailed race analysis in this study shows that the time in the last section prior to shooting relative to the overall lap time was inversely correlated to total XC skiing time on lap 2 and 3. This means that faster skiers generally employed higher speed through the entire laps 2 and 3, but that they paced slower toward standing shooting compared to slower skiers. This pacing strategy fits well to the fact that biathletes miss more in the standing position than in prone. It also means that slower biathletes should carefully evaluate race tactics concerning the approach to the shooting range. A possible limitation of our approach is the use of a GPS watch with 1-Hz sampling frequency that has some accuracy limitations in comparison to high-end GNSS-systems (e.g., a 10 Hz standalone GNSS receiver or a differential GNSS; Gløersen et al., 2018). However, attaching standalone high-accuracy GNSS-units onto the biathletes was not an option in this case, as we have not been able to identify a mounting solution that the top elite biathletes find acceptable for high-level competitions. Also, a recent study (Gløersen et al., 2018) where the applied GPS watches were validated indicates sufficient accuracy for our approach. Still, future field-based studies in biathlon should aim to apply higher-accuracy GPS-systems in combination with more advanced sensor technology (e.g., accelerometers and gyroscopes) to gain further knowledge of the competitive demands in biathlon.

Shooting Performance

The biathletes in this study hit 91 ± 7 and 86 ± 6% of the targets in the prone and standing position, respectively, which is almost equal to the average shooting performance of Top-10 in the World Cup sprint races (Luchsinger et al., 2018). In line with these findings from the biathlon World Cup and Olympic Games, we found a ∼5% lower hit rate in the standing compared to the prone position, which was accompanied by a 23% longer penalty time. Thus, most biathletes lose more time due to missed targets in the standing position than in prone in the biathlon sprint competition.

The biathletes' skiing intensities found here are also in line with previous findings of biathlon competitions (Hoffman and Street, 1992). Thus, the biathletes approach the shooting range with similar physiological response as seen 25 years earlier. However, here we found a smaller decrease in %HR_{max} during shooting than reported by Hoffman and Street (1992), which is probably explained by shorter shooting times employed by the biathletes in our study compared to the group of biathletes studied by Hoffmann and Street in 1992. The greater reduction in HR in prone compared to standing position found in this study was also in agreement with Hoffman and Street (1992), which is likely explained by the 13% longer shooting time in prone position in combination with higher HR in upright compared to supine position. The reduction in HR during shooting also puts different demands to the different shots fired in a 5-shot-series and the high HR on the first shot

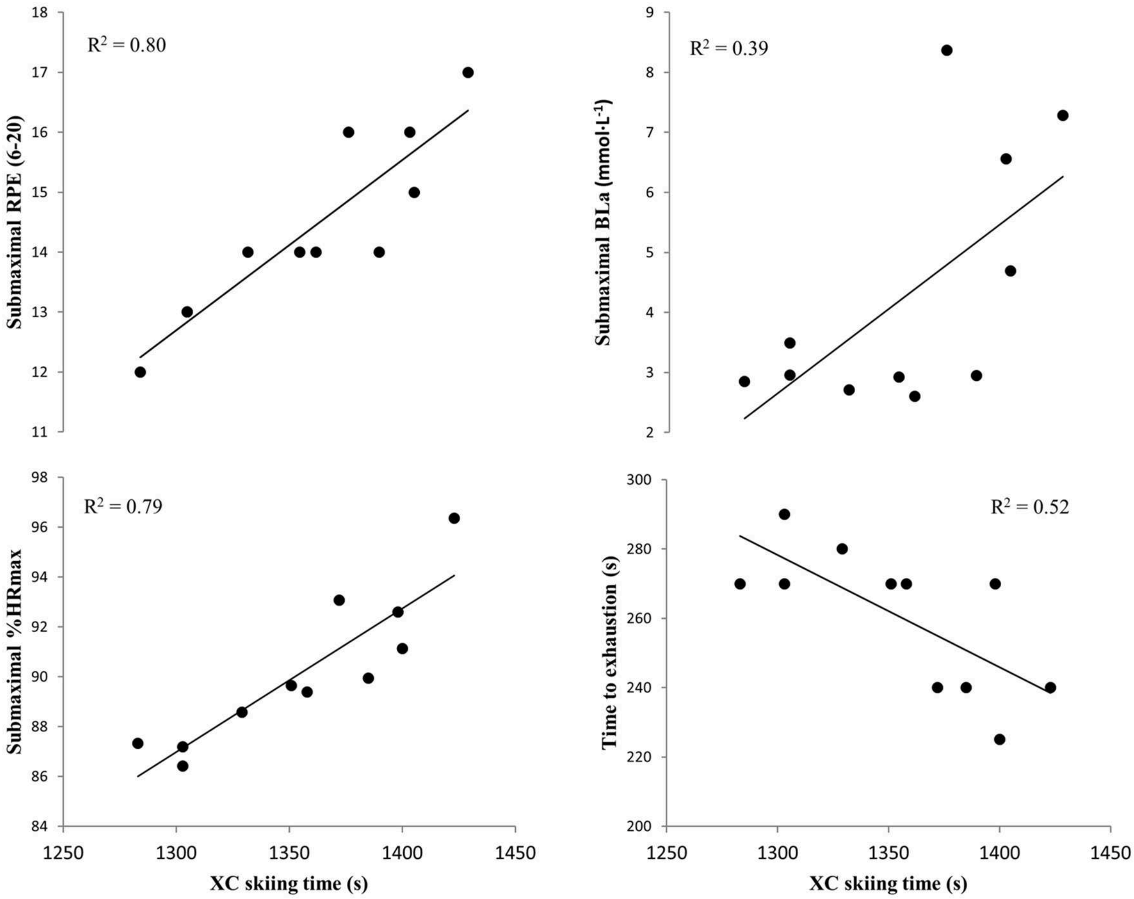

FIGURE 5 | Cross-country (XC) skiing time in relationship to rating of perceived exertion (RPE), relative heart rate (%HR_{max}), blood lactate concentrations (BLa) during submaximal roller skiing using the G2 sub-technique, and time to exhaustion during maximal roller skiing among 11 elite male biathletes. Presented with individual data points and trend lines based on linear regression.

could probably be one reason why biathletes miss the first shot twice as much as the second or third shot during prone shooting in biathlon World Cup sprint races (Luchsinger et al., 2018).

In another study, Hoffman et al. (1992) demonstrated that the exercise intensity negatively influenced parameters related to shooting technique in the standing position but to a lesser extent in prone position. Although no correlation between exercise intensity and shooting performance was seen for any of the shooting positions in our study, this might be explained by the relatively high hit rates and few mistakes to base the statistical tests on. In the future, more detailed analysis of the biathletes' hit points (i.e., measured as distance from center or group diameter) could probably provide additional information on the effect of exercise intensity and the risk of misses at the shooting range. Indeed, Hoffman et al. (1992) showed that hit rate was not affected by exercise intensity, whereas several detailed parameters related to shooting performance such as wobble diameter (movement of the rifle 1 s prior to trigger pull) and the spread of hits (mm) increased with higher exercise intensity, especially in the standing position. Thus, it might be that more detailed analysis of the spread of hits would reveal other relationships to exercise intensity than in our study. Interestingly, it has been suggested that the most important parameters of biathlon shooting technique are movement of the rifle in the vertical direction and cleanness of triggering (i.e., movement of the rifle 0.2–0.0 s before triggering; Ihalainen et al., 2018). This study additionally found that these parameters were negatively affected by high intensity exercise in both junior and elite biathletes, but that elite biathletes scored better than juniors on these technique parameters (Ihalainen et al., 2018). Altogether this indicates that biathletes' shooting technique is altered more by intense exercise than what can be seen on shooting performance measured as number of hits during a competition. This highlights the importance of combining laboratory designed studies with ecologically valid studies measuring actual biathlon race performance. Therefore, further research should examine the relationship between pacing toward shooting and detailed shooting performance (i.e., measure movement of the rifle, spread of hits) through designs that are more experimental in nature.

TABLE 5 | Correlations between physiological and performance variables obtained during submaximal and maximal roller skiing and the different XC skiing components among 11 elite male biathletes.

	Total time (s)	XC time (s)	Uphill terrain (s)	Varied terrain (s)	Downhill terrain (s)
Submaximal G4					
VO_2 ($L \cdot min^{-1}$)	−0.07	0.07	0.17	−0.27	0.17
VO_2 ($mL \cdot min^{-1} \cdot kg^{-1}$)	0.05	0.16	0.16	−0.02	0.34
VO_2 in % VO_{2peak}	0.26	0.29	0.25	0.13	0.55
HR ($beats \cdot min^{-1}$)	0.28	0.07	−0.05	0.34	0.15
HR in % of HR_{max}	0.91**	0.89**	0.87**	0.71*	0.58
RPE (6-20)	0.81**	0.93**	0.95**	0.64*	0.57
BLa ($mmol \cdot L^{-1}$)	0.45	0.49	0.43	0.35	0.63*
GE (%)	−0.05	−0.11	−0.15	0.09	−0.19
Submaximal G3					
VO_2 ($L \cdot min^{-1}$)	−0.00	0.17	0.28	−0.21	0.12
VO_2 ($mL \cdot min^{-1} \cdot kg^{-1}$)	0.18	0.30	0.34	0.11	0.33
VO_2 in % VO_{2peak}	0.40	0.43	0.39	0.26	0.58
HR ($beats \cdot min^{-1}$)	0.31	0.14	0.00	0.37	0.27
HR in % of HR_{max}	0.85**	0.89**	0.87**	0.67*	0.69*
RPE (6-20)[b]	0.76**	0.84**	0.82**	0.58*	0.71*
BLa ($mmol \cdot L^{-1}$)	0.51	0.61*	0.53	0.48	0.78**
GE (%)	−0.19	−0.31	−0.37	−0.07	−0.21
Submaximal G2					
VO_2 ($L \cdot min^{-1}$)	0.02	0.29	0.37	−0.07	0.28
VO_2 ($mL \cdot min^{-1} \cdot kg^{-1}$)	0.19	0.46	0.44	0.26	0.54
VO_2 in % VO_{2peak}	0.39	0.53	0.47	0.36	0.72*
HR ($beats \cdot min^{-1}$)	0.27	0.13	−0.01	0.37	0.30
HR in % of HR_{max}	0.80**	0.89**	0.85**	0.67*	0.73*
RPE (6-20)	0.80**	0.90**	0.86**	0.70*	0.70*
BLa ($mmol \cdot L^{-1}$)	0.46	0.63*	0.56	0.46	0.75**
GE (%)	−0.21	−0.48	−0.50	−0.23	−0.44
Maximal roller skiing					
VO_{2peak} ($L \cdot min^{-1}$)	−0.25	−0.11	−0.01	−0.30	−0.16
VO_{2peak} ($mL \cdot min^{-1} \cdot kg^{-1}$)	−0.22	−0.16	−0.12	−0.14	−0.30
TTE (s)	−0.67*	−0.72*	−0.56	−0.75**	−0.85**

*VO_2, oxygen uptake; HR, heart rate; HR_{max}, maximal heart rate based on outdoor tests from the year prior to this study; RPE, rating of perceived exertion; BLa, blood lactate concentration; GE, gross efficiency; VO_{2peak}, peak oxygen uptake from incremental test to exhaustion; TTE, time to exhaustion. *$p < 0.05$, **$p < 0.01$.*

Laboratory Determinants Associated With XC Skiing Performance

The predictive values of RPE and $\%HR_{max}$ during submaximal roller skiing for XC skiing time and time spent in different terrains were significant for all three sub-techniques. In addition, lower blood lactate concentrations in the G3 and G2 sub-techniques were positively correlated to better XC skiing performance and time spent in downhill terrain. Together, this indicates that the submaximal stages were less demanding for the best performing biathletes in the competition. These findings are in line with a study in cycling, indicating that submaximal measurements based on RPE revealed best relationships both with performance and changes in performance over time (Rodriguez-Marroyo et al., 2017). This highlights the relevance of simply measured variables, such as RPE and $\%HR_{max}$, to predict biathlon sprint race performance.

Blood lactate levels on the submaximal stages (performed in uphill terrain) were only correlated to downhill competition performance and not to uphill or varied terrain. This could be explained by the fact that athletes who are faster in the uphill sections are also able to maintain speed better in this terrain and thereby ski faster over hilltops, which subsequently provides higher speeds in the downhill sections. This theory is supported by findings in XC skiing, revealing higher variations in speed at the end of uphill sections and subsequent transition into downhill sections (Andersson et al., 2010), indicating the importance of skiing fast over hilltops in order to create speed in downhills. In addition, a recent study of XC skiers indicate a lag in the physiological response after hilltops and strengthens the importance of being able to create speed at the top of each downhill section (Haugnes et al., 2019).The stronger association between XC skiing performance and RPE or $\%HR_{max}$ than the corresponding relationship with blood lactate concentration can likely be explained by the different physiological behavior of these variables; blood lactate concentration might be relatively similar between athletes of different performance levels at low submaximal speed (such as the aerobic steady-state conditions used here), whereas RPE and $\%HR_{max}$ would increase more linearly with increased individual load—and thereby be higher in lower level athletes at the same speed.

The submaximal oxygen cost and GE did not correlate to XC skiing performance in this biathlon sprint competition, which is in contrast to studies in the skating technique in XC skiing (Sandbakk et al., 2010, 2011b, 2013). This means that faster biathletes, who are able to ski on a lower $\%HR_{max}$ and RPE on the submaximal stages, are not more efficient than lower level biathletes, indicating that additional factors than efficiency would explain the differences in XC skiing performance levels. The most likely explanatory factor is that better XC skiers with similar efficiencies have higher "maximal capacities," which was also indicated here by the longer TTE of faster skiers. However, VO_{2peak} did not correlate with XC skiing performance in this study, and other factors than measured in our design must have contributed to explain the performance differences in XC skiing both on the field and during the treadmill test. This could be factors such as indices of the anaerobic threshold (which subsequently would allow skiers to compete on a higher fraction of their "maximal capacity") or anaerobic energy delivery capacity. Therefore, a possible limitation of our approach is the lack of additional physiological measurements (e.g., lactate threshold). The fact that biathletes stop during shooting and have shorter loops of skiing than normally employed in cross-country skiing could imply that biathletes to a greater extent than cross-country skiers must be able to accelerate from more stops during a race and create faster speeds through more turns and smaller but more uphills. However, analyses of the differences between course profiles in XC skiing and biathlon are lacking so the latter assumption remains unknown.

The submaximal stages using different sub-techniques were performed both with and without carrying a rifle, but the order of the stages was not randomized since our purpose was to correlate physiological and perceptual responses with race performance and not to examine the effects of carrying a rifle *per se*. However, the observed correlations did not change when using measurements without carrying a rifle, despite the associated increase in submaximal oxygen cost, HR and blood lactate concentrations compared to roller skiing without the rifle. This indicates relatively robust results in these cases.

Performance in the laboratory, measured as TTE, correlated to overall biathlon sprint race performance, XC skiing time on the last lap and time spent in varied and downhill terrains. When correlated separately with performance on each lap, TTE correlated strongly with performance on the last lap, but not with the first or the second lap. This indicates that better performing athletes in the laboratory adjust their pacing on the two first laps before shooting, which is different from XC skiing, where skiers generally use a more positive pacing than in biathlon. TTE during treadmill roller skiing has also been shown to correlate with on-snow performance in elite XC skiers (Sandbakk et al., 2011a). Hence, this emphasizes the relevance of determining performance by an incremental test to exhaustion in the laboratory when monitoring the development of biathletes' performance level. In addition, it indicates that better performing athletes use different pacing strategies than their lower level peers.

In the current study, no significant associations were identified between VO_{2peak} and XC skiing time, nor time spent in different terrains. These findings are in agreement with Rundell and Bacharach (1995), who showed that TTE during treadmill running and performance during a 1 km double-poling time-trial on snow correlated significantly with performance during a biathlon sprint race among men, whereas VO_{2peak} did not. In contrast, previous observations in XC skiing highlight VO_{2peak} as a key determinant of performance (Sandbakk and Holmberg, 2017). The reason for these somewhat conflicting findings are not known but could be explained by differences in the heterogeneity of groups in the different studies or different demands in XC skiing compared to biathlon. However, the average VO_{2peak} among the participants in our study is lower than was previously found in Olympic- or World Championship medalists in biathlon (Tønnessen et al., 2015). In addition, the stages of rifle shooting, leading to periods of ∼60–90 s with a reduction in exercise intensity toward shooting in addition to the time spent at the shooting range make biathlon competitions even more interval-based than in XC skiing and pacing strategies may play a more important role.

CONCLUSION

The present study showed that XC skiing performance provides greatest impact on overall biathlon sprint performance, with 84% of the variance being explained by this component and most of the variance determined by the time spent in the uphill terrain sections. Overall, this indicates that biathletes should emphasize the development of their XC skiing performance to perform well in biathlon sprint competitions. Although biathletes need to ski fast in all types of terrain, improvements in uphill-specific performance seem to have a particular impact on the overall performance in the biathlon sprint competition. While shooting performance in general is an important component in biathlon, it had clearly lower importance than XC skiing in this study, where penalty time explained 14% of the remaining variance in overall sprint race performance and shooting time and range time together only 2% of the final variance. In addition, race tactics and pacing are important aspects in biathlon competitions and our data indicate a further potential to enhance performance by optimizing pacing strategies, especially among the slower skiers who lose most time on the last lap to the faster skiers.

Based on treadmill roller ski tests in the laboratory, lower ratings of RPE and $\%HR_{max}$ during submaximal roller skiing in the three main sub-techniques of skating, as well as longer TTE during an incremental test to exhaustion, were strongly correlated to overall biathlon sprint performance and XC skiing time. Such laboratory-derived measures may therefore be validly used to distinguish biathletes of different performance levels and to track progress of their XC skiing capacity. In contrast, the non-significant relationships to peak oxygen uptake and gross efficiency indicate that other variables than those measured here (such as anaerobic capacity) also contributed to TTE and biathlon performance in these athletes.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

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 patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

All authors contributed in the design of the study. HL and RT collected the data. JK performed the data handling of GPS and HR-signals. RT performed the statistical analyses. All authors contributed to the writing of the manuscript and to the design of figures and tables.

ACKNOWLEDGMENTS

The authors would like to thank the athletes and their coaches for enthusiastic cooperation and participation in the study. This work was carried out without the presence of any personal, professional, or financial relationships that could potentially be construed as a conflict of interest.

REFERENCES

Andersson, E., Supej, M., Sandbakk, Ø., Sperlich, B., Stöggl, T., and Holmberg, H. C. (2010). Analysis of sprint cross-country skiing using a differential global navigation satellite system. *Eur. J. Appl. Physiol.* 110, 585–595. doi: 10.1007/s00421-010-1535-2

Biathlon (2017). *Norwegian Biathlon Association Official Results 2017-2018 season [Online].* Avaiable online at: http://www.skiskyting.no/ (accessed December 1, 2017).

Bolger, C. M., Kocbach, J., Hegge, A. M., and Sandbakk, Ø. (2015). Speed and heart-rate profiles in skating and classical cross-country skiing competitions. *Int. J. Sports Physiol. Perform.* 10, 873–880. doi: 10.1123/ijspp.2014-0335

Borg, G.A. (1982). Psychophysical bases of perceived exertion. *Med. Sci. Sports Exerc.* 14, 377–381. doi: 10.1249/00005768-198205000-00012

FIS (2017). *International Ski Federation Homologations [Online].* Avaiable online at: http://www.fis-ski.com/ (accessed December 1, 2017).

Gløersen, Ø., Kocbach, J., and Gilgien, M. (2018). Tracking performance in endurance racing sports: evaluation of the accuracy offered by three commercial GNSS receivers aimed at the sports market. *Front. Physiol.* 9:1425. doi: 10.3389/fphys.2018.01425

Haugnes, P., Kocbach, J., Luchsinger, H., Ettema, G., and Sandbakk, Ø. (2019). The interval-based physiological and mechanical demands of cross-country ski training. *Int. J. Sports Physiol. Perform.* 1–23. doi: 10.1123/ijspp.2018-1007. [Epub ahead of print]

Hoffman, M. D., Gilson, P. M., Westenburg, T. M., and Spencer, W. A. (1992). Biathlon shooting performance after exercise of different intensities. *Int. J. Sports Med.* 13, 270–273. doi: 10.1055/s-2007-1021265

Hoffman, M. D., and Street, G. M. (1992). Characterization of the heart rate response during biathlon. *Int. J. Sports Med.* 13, 390–394. doi: 10.1055/s-2007-1021286

IBU (2017). *International Biathlon Union Rules and Description of Biathlon Competitions [Online].* Avaiable online at: http://www.biathlonworld.com/ (accessed December 1,2017).

Ihalainen, S., Laaksonen, M. S., Kuitunen, S., Leppavuori, A., Mikkola, J., Lindinger, S. J., et al. (2018). Technical determinants of biathlon standing shooting performance before and after race simulation. *Scand. J. Med. Sci. Sports* 28, 1700–1707. doi: 10.1111/sms.13072

Laaksonen, M. S., Finkenzeller, T., Holmberg, H.-C., and Sattlecker, G. (2018a). The influence of physiobiomechanical parameters, technical aspects of shooting, and psychophysiological factors on biathlon performance: a review. *J. Sport Health Sci.* 7, 394–404. doi: 10.1016/j.jshs.2018.09.003

Laaksonen, M. S., Jonsson, M., and Holmberg, H.-C. (2018b). The olympic biathlon - recent advances and perspectives after pyeongchang. *Front. Physiol.* 9:796. doi: 10.3389/fphys.2018.00796

Losnegard, T. (2019). Energy system contribution during competitive cross-country skiing. *Eur. J. Appl. Physiol.* 119, 1675–1690. doi: 10.1007/s00421-019-04158-x

Losnegard, T., Kjeldsen, K., and Skattebo, Ø. (2016). An analysis of the pacing strategies adopted by elite cross-country skiers. *J. Strength Cond. Res.* 30, 3256–3260. doi: 10.1519/JSC.0000000000001424

Luchsinger, H., Kocbach, J., Ettema, G., and Sandbakk, Ø. (2018). Comparison of the effects of performance level and sex on sprint performance in the Biathlon World Cup. *Int. J. Sports Physiol. Perform.* 13, 360–366. doi: 10.1123/ijspp.2017-0112

Peronnet, F., and Massicotte, D. (1991). Table of nonprotein respiratory quotient: an update. *Can. J. Sport Sci.* 16, 23–29.

Rasdal, V., Fudel, R., Kocbach, J., Moen, F., Ettema, G., and Sandbakk, Ø. (2017). Association between laboratory capacities and world-cup performance in Nordic combined. *PLoS ONE* 12:e0180388. doi: 10.1371/journal.pone.0180388

Rodriguez-Marroyo, J. A., Pernia, R., Villa, J. G., and Foster, C. (2017). Reliability and seasonal changes of submaximal variables to evaluate professional cyclists. *Int. J. Sports Physiol. Perform.* 12, 1356–1362. doi: 10.1123/ijspp.2016-0435

Rundell, K. W. (1995). Treadmill roller ski test predicts biathlon roller ski race results of elite U.S. Biathlon women. *Med. Sci. Sports Exerc.* 27, 1677–1685. doi: 10.1249/00005768-199512000-00015

Rundell, K. W., and Bacharach, D. W. (1995). Physiological characteristics and performance of top U.S. biathletes. *Med. Sci. Sports Exerc.* 27, 1302–1310. doi: 10.1249/00005768-199509000-00010

Sandbakk, Ø., Ettema, G., Leirdal, S., Jakobsen, V., and Holmberg, H. C. (2011a). Analysis of a sprint ski race and associated laboratory determinants of world-class performance. *Eur. J. Appl. Physiol.* 111, 947–957. doi: 10.1007/s00421-010-1719-9

Sandbakk, Ø., Hegge, A. M., and Ettema, G. (2013). The role of incline, performance level, and gender on the gross mechanical efficiency of roller ski skating. *Front. Physiol.* 4:293. doi: 10.3389/fphys.2013.00293

Sandbakk, Ø., Hegge, A. M., Losnegard, T., Skattebo, Ø., Tonnessen, E., and Holmberg, H. C. (2016a). The physiological capacity of the world's highest ranked female cross-country skiers. *Med. Sci. Sports Exerc.* 48, 1091–1100. doi: 10.1249/MSS.0000000000000862

Sandbakk, Ø., and Holmberg, H. C. (2014). A reappraisal of success factors for Olympic cross-country skiing. *Int. J. Sports Physiol. Perform.* 9, 117–121. doi: 10.1123/ijspp.2013-0373

Sandbakk, Ø., and Holmberg, H. C. (2017). Physiological capacity and training routines of elite cross-country skiers: approaching the upper limits of human endurance. *Int. J. Sports Physiol. Perform.* 12, 1–26. doi: 10.1123/ijspp.2016-0749

Sandbakk, Ø., Holmberg, H. C., Leirdal, S., and Ettema, G. (2010). Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers. *Eur. J. Appl. Physiol.* 109, 473–481. doi: 10.1007/s00421-010-1372-3

Sandbakk, Ø., Holmberg, H. C., Leirdal, S., and Ettema, G. (2011b). The physiology of world-class sprint skiers. *Scand. J. Med. Sci. Sports* 21, e9–e16. doi: 10.1111/j.1600-0838.2010.01117.x

Sandbakk, Ø., Losnegard, T., Skattebo, Ø., Hegge, A. M., Tønnessen, E., and Kocbach, J. (2016b). Analysis of classical time-trial performance and technique-specific physiological determinants in elite female cross-country skiers. *Front. Physiol.* 7:326. doi: 10.3389/fphys.2016.00326

Sandbakk, Ø., Rasdal, V., Bråten, S., Moen, F., and Ettema, G. (2016c). How do world-class nordic combined athletes differ from specialized cross-country skiers and ski jumpers in sport-specific capacity and training characteristics? *Int. J. Sports Physiol. Perform.* 11, 899–906. doi: 10.1123/ijspp.2015-0285

Skattebo, Ø., and Losnegard, T. (2017). Variability, predictability and race factors affecting performance in elite biathlon. *Int. J. Sports Physiol. Perform.* 13, 313–319. doi: 10.1123/ijspp.2017-0090

Solli, G. S., Kocbach, J., Seeberg, T. M., Tjønnås, J., Rindal, O., Haugnes, P., et al. (2018). Sex-based differences in speed, sub-technique selection, and kinematic patterns during low- and high-intensity training for classical cross-country skiing. *PLoS ONE* 13:e0207195. doi: 10.1371/journal.pone.0207195

Stöggl, T., Bishop, P., Hook, M., Willis, S., and Holmberg, H. C. (2015). Effect of carrying a rifle on physiology and biomechanical responses in biathletes. *Med. Sci. Sports Exerc.* 47, 617–624. doi: 10.1249/MSS.0000000000000438

Tønnessen, E., Haugen, T. A., Hem, E., Leirstein, S., and Seiler, S. (2015). Maximal aerobic capacity in the winter olympic endurance disciplines: olympic medal benchmarks for the time period 1990-2013. *Int. J. Sports Physiol. Perform.* 10, 835–839. doi: 10.1123/ijspp.2014-0431

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.

frontiers in Sports and Active Living

PERSPECTIVE
published: 22 January 2020
doi: 10.3389/fspor.2019.00074

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Methodological and Practical Considerations Associated With Assessment of Alpine Skiing Performance Using Global Navigation Satellite Systems

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OPEN ACCESS

Edited by:
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Reviewed by:
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Frederic Nicolas Puel, Université de Reims Champagne-Ardenne, France

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Specialty section:
This article was submitted to Sports Science, Technology and Engineering, a section of the journal Frontiers in Sports and Active Living

Received: *27 September 2019*
Accepted: *24 December 2019*
Published: *22 January 2020*

Citation:
Supej M, Spörri J and Holmberg H-C (2020) Methodological and Practical Considerations Associated With Assessment of Alpine Skiing Performance Using Global Navigation Satellite Systems. Front. Sports Act. Living 1:74. doi: 10.3389/fspor.2019.00074

Reliable assessment of the performance of alpine skiers is essential. Previous studies have highlighted the potential of Global Navigation Satellite Systems (GNSS) for evaluating this performance. Accordingly, the present perspective summarizes published research concerning methodological and practical aspects of the assessment of alpine skiing performance by GNSS. Methodologically, in connection with trajectory analysis, a resolution of 1–10 cm, which can be achieved with the most advanced GNSS systems, has proven to provide acceptable accuracy. The antenna should be positioned to follow the trajectory of the skier's center-of-mass (CoM) as closely as possible and estimation of this trajectory can be further improved by applying advanced modeling and/or other computerized approaches. From a practical point of view, effective assessment requires consideration of numerous parameters related to performance, including gate-to-gate times, trajectory, speed, and energy dissipation. For an analysis that is both more comprehensive and more easily accessible to coaches/athletes, video filming should be synchronized with the GNSS data. In summary, recent advances in GNSS technology already allow, at least to some extent, precise biomechanical analysis of performance over an entire alpine skiing race course in real-time. Such feedback has both facilitated and improved the work of coaches. Thus, athletes and coaches are becoming more and more aware of the advantages of analyzing alpine skiing performance by GNSS in combination with advanced computer software, paving the way for the digital revolution in both the applied research on and practice of this sport.

Keywords: Galileo, GPS, GLONASS, biomechanics, trajectory, speed, velocity, energy dissipation

INTRODUCTION

In outdoor sports such as alpine skiing, valid and reliable assessment of performance in the field is essential, but, at the same time, quite challenging. For finding answers to many questions concerning performance, experiments under representative real-life conditions are indispensable and standardized procedures employing the latest advances in wearable technologies are central in this context. Previous studies have highlighted the considerable potential of Global Navigation Satellite Systems (GNSS) for evaluating alpine skiing performance based on monitoring of parameters such as time, speed and mechanical energy (Brodie et al., 2008b; Supej, 2010; Supej and Holmberg, 2011; Supej et al., 2013; Gilgien et al., 2014a, 2015a,b, 2016; Fasel et al., 2016; Kröll et al., 2016). The application of such technologies should allow both researchers and coaches to analyze the patterns of motion/tactics of athletes in depth and test sports equipment thoroughly.

Although alpine skiing performance can be characterized in terms of a variety of different biomechanical parameters, skiing from the start to the finish line as rapidly as possible is the obvious ultimate goal set by the International Ski Federation (FIS, 2016). Performance can be improved in many ways, but a skier can spend years attempting to gain a few hundredths of a second, which often make the difference between winning an Olympic medal or not. Nonetheless, the time spent on shorter sections of an alpine racing course can vary as much as 10%, even among the fastest skiers (Supej and Cernigoj, 2006), so there is considerable room for improving sectional performance.

Continuous adaptation of turning technique to changes in terrain, slopes, gate setup, and snow conditions is technically complex and requires assessment of parameters of performance that are more detailed and nuanced than simple overall race time (Supej, 2008; Supej et al., 2011; Federolf, 2012; Spörri et al., 2018). However, such analyses are extremely challenging, since many kinematic and kinetic factors influence performance, directly or indirectly. The most obvious kinematic parameters include section time, determined by the skier's trajectory and velocity; while the kinetic parameters include aerodynamics, interaction between the skis and snow (Federolf, 2012; Hébert-Losier et al., 2014), and energy dissipation, this latter constituting the best indicator of both instantaneous and sectional performance (Supej, 2008; Supej et al., 2011; Spörri et al., 2018). At present, no analytical approach provides a straightforward explanation of the difference between the fastest and slowest turns (Spörri et al., 2012). Clearly, multiple parameters must be monitored simultaneously.

Assessment of appropriate biomechanical parameters with modern wearable technology (such as the GNSS) can reveal minor, but nonetheless essential details concerning alpine skiing performance. Importantly, GNSS technology provides data quite rapidly, feasibly in real-time. However, insufficient accuracy and/or invalid methodology may lead to incorrect conclusions and reliable methodological advice concerning techniques, tactics and equipment is obviously a necessity. Accordingly, this commentary focuses on published research concerning methodological and practical considerations associated with the assessment of alpine skiing performance by GNSS.

PRACTICAL CONSIDERATIONS

The multitude of biomechanical factors reported to influence performance include sectional or overall times, trajectory of the skis and/or of the center of mass, energy, ground reaction forces, aerodynamic drag, and frictional forces (Hébert-Losier et al., 2014). GNSS technology disturbs the skiers very little and is relatively easy to install and, therefore, has been applied extensively in assessing the performance of alpine skiers.

Kinematic Parameters of Performance

In connection with competitive alpine skiing, accurate determination of section time is essential (Supej and Holmberg, 2011). To achieve the shortest overall time on a course, the skier should (1) lose as little time as possible on his/her weakest sections and gain as much as possible on the strong sections or (2) strive for his/her best time on each and every section (Supej and Cernigoj, 2006; Hébert-Losier et al., 2014). By determining gate positions and the skier's trajectory, GNSS technology enables assessment of gate-to-gate time with pronounced accuracy and validity (as compared to photocells) and no systematic bias, as well as an error that declines at higher velocities (Supej and Holmberg, 2011). Furthermore, multiple comparisons of gate-to-gate and lag times have demonstrated that GNSS enables much more detailed analysis than routine usage of photocells.

However, evaluation of performance on the basis of racing time alone, even on short sections of a course, involves several limitations (Supej, 2008). First, this time is influenced by the skier's initial velocity, position, and orientation. Secondly, the position and orientation at the end of a section relative to the following gate, as well as the exit speed will exert little influence on section time, but may affect subsequent performance profoundly. Third, such chronological information about when the skier is present at the initial and final positions of a section cannot explain why one skier is faster than another. Accordingly, other measures of performance are required.

In addition to racing time, skiing trajectory can also be analyzed by GNSS. In general, skiing the shortest possible trajectory rapidly results in the fastest time, but is often connected with higher energy losses (Supej, 2008; Federolf, 2012; Spörri et al., 2018). The ability to maintain high speed depends not only on the trajectory, but also on the skier's technique and choice of trajectory. Accordingly, valuable insights that improve performance can be gained by monitoring gate-to-gate times and velocities in order to analyze parameters related to skiing trajectory, such as whether the turn is started/ended at a higher or lower position in relationship to the gate or whether the trajectory is direct or more wider/rounded (Brodie et al., 2008a; Supej, 2008, 2012; Federolf, 2012; Spörri et al., 2012, 2018). This approach can also be of considerable value in connection with testing equipment (e.g., skis, ski boots), which in a broader sense is closely related to performance.

Kinetic Parameters of Performance

Aerodynamic drag and ski–snow friction are the only two mechanical forces that can exert a detrimental impact on skiing performance (von Hertzen et al., 1997; Federolf et al., 2008; Meyer et al., 2012; Supej et al., 2013). When skiing downhill, aerodynamic drag accounts for almost 50% of the differences in racing time between slower and faster alpine skiers (Luethi and Denoth, 1987); whereas in the case of giant slalom, this drag causes only 15% of the total energy loss per turn and is not considered a major determinant of performance (Supej et al., 2013). The aerodynamic drag becomes more important as the speed increases (e.g., from slalom to downhill) (Gilgien et al., 2013, 2018). The opposite is true for ski-snow friction, which is more important at slower speeds, particularly when turning. During slalom and giant slalom, the ski-snow friction dissipates most of the energy (Supej et al., 2013). Even in the speed disciplines, involving more intense turning, the skiers focus more on guiding the skis smoothly than minimizing the frontal area exposed.

GNSS technology has been successfully applied to characterize aerodynamic drag (Gilgien et al., 2013; Supej et al., 2013) and ski-snow friction (Gilgien et al., 2013), as well as to estimate ground reaction forces during giant slalom, super-G, and downhill (Gilgien et al., 2014a). However, although this technology in combination with advanced computation and modeling, including double differentiation, is particularly suitable for investigating large differences between disciplines, such methodology is probably less able to detect small differences in performance.

Since aerodynamic drag makes only a small contribution to overall energy dissipation in the technical disciplines (giant slalom and slalom), it appears advisable to utilize overall energy dissipation, which is less prone to computational error, to assess performance in these cases (Supej, 2008; Supej et al., 2011). Moreover, as already discussed above, timing over a short section depends strongly on the performance in the preceding section (Supej et al., 2011) and the speed itself may change due to changes in, e.g., inclination. Therefore, analysis of energy, a more integral kinetic parameter, can improve evaluation of performance.

To summarize, no individual biomechanical parameter can explain *why* one skier is faster than another (Hébert-Losier et al., 2014). Kinematic parameters reflect more the outcome of performance (i.e., without consideration of cause), whereas kinetic parameters may provide insight into the underlying causes. Thus, successful skiers need to exploit the intricate interactions between biomechanical parameters and technique under varying conditions in a manner that minimizes section and/or overall race times.

METHODOLOGICAL CONSIDERATIONS

Validity and Reliability

GNSS in combination with integrated accelerometers has been applied extensively to a variety of sports during the past decade, e.g., for measuring the running velocity of team-sport players, both during matches and training (Johnston et al., 2012, 2014; Varley et al., 2012, 2014; Hoppe et al., 2018). Moreover, numerous investigations have focused on the validity and reliability of such systems for determining acceleration and/or speed during various forms of locomotion (Schutz and Herren, 2000; Townshend et al., 2008; Barbero-Alvarez et al., 2010; Coutts and Duffield, 2010; Aughey, 2011; Waldron et al., 2011; Varley et al., 2012; Akenhead et al., 2014; Johnston et al., 2014; Scott et al., 2016; Nagahara et al., 2017; Roe et al., 2017; Hoppe et al., 2018), utilizing photocells as the "golden standard" in most cases. Unfortunately, most such studies have not assessed velocities of relevance to competitive alpine skiing.

In the case of running, the validity and reliability of commercially available GNSS systems, even those of the same brand, is influenced by a number of factors. The slower the sample rate (Coutts and Duffield, 2010; Aughey, 2011; Varley et al., 2012), higher the velocity (Petersen et al., 2009; Jennings et al., 2010; Johnston et al., 2012), shorter the duration of activity (Petersen et al., 2009; Coutts and Duffield, 2010) and greater the number of changes in direction (Duffield et al., 2010; Jennings et al., 2010), the lower the validity and reliability of GNSS data. For example, a reduction in sampling frequency from 10 to 5 Hz can elevate both the standard error and coefficient of variation two- to three-fold (Waldron et al., 2011). On the other hand, even inexpensive GNSS systems measure speed with considerable accuracy, especially at lower acceleration (Supej and Cuk, 2014). Furthermore, real-time assessments with GNSS and/or synchronization of this technology with others (e.g., Inertial Motion Unit; IMU) requires caution, because of the pronounced latency of inexpensive systems, particularly those sampling at 1 Hz. In this context, it should be noted that the systems employed should be selected carefully, since some products advertise higher sampling rates that provide little or no benefit in practice (Haugen and Buchheit, 2016). On the other hand, a previous study proposed that supplementing GNSS with inexpensive and light-weight accelerometers offers a cheap and promising alternative with which to improve sampling rates and accuracy (Waegli et al., 2009).

At the same time, the validity and reliability of GNSS can be improved by employing high-quality differential/real-time kinematics (RTK) systems (Gilgien et al., 2014b), as is more often done in investigations on alpine skiing (Supej et al., 2008, 2013; Supej, 2010; Supej and Holmberg, 2011; Gilgien et al., 2013, 2015a,b, 2016, 2018). In fact, with their highest accuracy and applicability, RTK GNSS systems represent the "golden standard" for alpine skiing. In most studies on alpine skiing, an acceptable accuracy for trajectory analysis has proven to be 1–10 cm, at least when examining the technical disciplines (slalom and giant slalom), where gate distances and differences in trajectory are smaller than in the speed disciplines. Such great accuracy can only be achieved with differential, GPS+GLONASS (the United States plus the Russian global navigation satellite systems) and dual frequency GNSS systems (Gilgien et al., 2014b), working either in real-time (RTK) or post-processing kinematic mode. Improvements in the sensitivity of the receivers, an increase in the number of satellites, and development of tracking on multiple frequencies (e.g., the Galileo GNSS has four) are enhancing the position accuracy of newer, less expensive systems (GalileoGNSS, 2018).

Most high-quality RTK systems provide sampling rates of 10–20 Hz, sometimes as high as 100 Hz; however, based on our own experience, at such high frequencies accuracy is often compromised. In addition, even with optimal satellite visibility and accuracy on the order of 1 centimeter, monitoring of position at 100 Hz results in a high noise-to-signal ratio[1] when determining, e.g., speed or, even worse, acceleration by double differentiation. This noise then needs to be filtered out by proper algorithms, most often using restrictive low-pass digital filters, which render such high sampling frequencies of questionable value.

Finally, to ensure optimal precision, the use of geometric dilution of precision (GDOP) and visible satellites with a sufficiently broad azimuth angle is advisable (Supej and Holmberg, 2011), since measurements are affected by the constantly changing constellation of the satellites involved (Parkinson and Spilker, 1996). Furthermore, during analysis of performance, the error for each position on the trajectory surveyed must be determined, since with GNSS technology this error may change rapidly.

Positioning Antenna in Relationship to the Skier's Center-of-Mass

The major drawback of a single GNSS unit is that only a single trajectory, i.e., the path of the antenna, can be monitored. Obviously, placing the antenna on the skier's center-of-mass (CoM), from a biomechanical perspective probably the most interesting position to track, is quite difficult. Most commonly, the antenna is positioned either on the neck (in the vicinity of the upper thoracic spine) (Supej et al., 2008, 2013; Supej, 2010, 2012; Supej and Holmberg, 2011; Nemec et al., 2014) or on top of the head (typically on the helmet) (Gilgien et al., 2013, 2015a,b, 2016, 2018). Each of these placements has certain advantages and disadvantages: the antenna on the neck is closer to the CoM, but satellite visibility may be restricted. In contrast, placement on the head usually provides better satellite visibility, but the antenna is then further from the CoM, with a longer lever, while also restricting head movement and elevating the torque on the skier's neck in connection with rapid acceleration during turning, landing or similar actions. Placing multiple antennae on the skier in order to monitor the position of the CoM more accurately is not advisable, because this will reduce satellite visibility in the case of antennae positioned below the shoulders and wearable systems that are sufficiently accurate (e.g., RTK GNSS) are also bulky. Therefore, placement of the antenna on the skis, as suggested by Seifriz et al. (2003), is, in our opinion, also not desirable, since this may in addition also interfere with the behavior of the skis.

To improve analysis of the kinematics of the CoM on the basis of positioning data provided by GNSS antennae, various approaches have been explored. Supej (2008) modeled the skier's body as a statically balanced inverted pendulum and then employed Kalman filtering to estimate the acceleration required to compute the equilibrium position of this pendulum. A similar calculation of the quasi-static equilibrium of an inverted pendulum has been proposed by Gilgien et al. (2015b). In addition, in order to estimate the COM while taking into consideration the influence of air drag during giant slalom skiing, this approach has been improved further by taking the dynamics of the inverted pendulum into account as well (Supej et al., 2013).

In comparison to video-based 3D kinematics (Gilgien et al., 2013, 2015b) and inertial systems (Nemec et al., 2014), such inverted pendulum models provide accurate results during the more rapid turning in the vicinity of gates, where radial forces are stronger, but poorer results during weight transitions, which involve weaker forces. Novel solutions to this problem that have been proposed include locally weighted projection regression and back-propagation neural networks designed to predict the skier's posture from the GNSS data (Nemec et al., 2014), both of which demonstrate errors of prediction substantially smaller than those obtained with inverted pendulum models. Moreover, these novel approaches are computationally less demanding, allowing utilization in real-time.

Alternatively, multiple inertial sensors in combination with GNSS can be used to monitor whole-body 3D kinematics during alpine skiing (Brodie et al., 2008a; Krüger and Edelmann-Nusser, 2010; Supej, 2010), enabling detailed analysis over the entire course. Accordingly, when the movement of fewer body segments or only of the CoM is of interest, the number of inertial sensors can be reduced (Fasel et al., 2016). Although usage of multiple inertial sensors in combination with GNSS is of considerable value in connection with advanced scientific research, its methodological complexity makes it impractical for monitoring performance in the field. Nevertheless, adding an accelerometer to assist RTK GNSS may also be used to help to navigate zones where GNSS signals are unreliable (Skaloud and Limpach, 2003).

Synchronizing GNSS With Video Recordings

Despite the many advantages of wearable GNSS technology, this technology alone does not provide feedback that is fully intuitive to athletes and their coaches. A relatively simple way to circumvent this difficulty is to combine video recordings with the GNSS. Qualitative visual information can greatly assist in the analysis of performance, especially since athletes and coaches routinely examine video recordings. For more advanced analysis, synchronization between the GNSS and video recording is necessary and this can be achieved with different types of hardware or even through simple body movements, such as squats (Supej, 2012).

FUTURE PERSPECTIVES

Again, it is worth noting that the differences in the race times of Olympic alpine skiers who take gold and silver medals are no more than hundredths of a second (e.g., 0.01 s in the case of the women's Super-G in the 2018 Pyeongchang Winter Olympics), rendering virtually all factors

[1]Monitoring two consecutive positions with a latitude accuracy of 1 cm and a sampling rate of 100 Hz is associated with a 2 m/s error in speed, which, after double differentiation, results in a 400 m/s^2 error in acceleration. In contrast, the same position accuracy at 20 Hz is associated with corresponding errors of 0.4 m/s and 16 m/s^2.

that influence performance extremely important. Although the technological ability to assess the biomechanics of alpine skiers has been improved substantially in recent decades, relatively little is yet known concerning optimization of performance over an entire course (Hébert-Losier et al., 2014) or about interactions between skiing on successive sections (Supej and Cernigoj, 2006). Recent advances in GNSS technology will and, to some extent, already do allow precise biomechanical analysis of performance over an entire race course in real-time (Supej et al., 2008, 2013; Supej, 2012; Gilgien et al., 2013), providing much more detailed information about such factors.

Continuous miniaturization of mechanical, electrical, and optical sensing technologies that enable assessment of the kinematics and kinetics of human motion and performance will lead to even more comfortable and flexible monitoring and assessment of the training load, technique, choice of trajectory and performance of alpine ski racers (Heikenfeld et al., 2018). In this connection, an innovative approach to estimating center-of-mass that involves fusing inertial sensors with anchor points that become available periodically has been proposed recently (Fasel et al., 2018). Further development of lighter and less bulky GNSS systems with accelerometers could provide a cheaper alternative to RTK systems in this context. More user-friendly and automated software involving artificial intelligence (machine learning, neural networks, and deep learning) in combination with wearable technology is expected to allow real-time feedback in the near future (Nemec et al., 2014). Therefore, coaches will need more technical and computer skills and/or expert assistance. Finally, in analyzing alpine skiing, both experts and coaches must become more aware of the possibilities offered by highly accurate GNSS.

CONCLUSIONS

Wearable technologies, especially GNSS, have been widely used in research on alpine skiers. The biomechanical feedback provided by such technologies has improved and facilitated the work of coaches. Many skiing teams occasionally or even regularly employ GNSS technology to assess skiing performance and test equipment. This approach can help identify minor, but important differences between athletes that cannot be detected by the naked eye, standard photocells or video analysis (e.g., gate-to-gate timing, comparison of gate-gate velocities, and precise analysis of trajectory). Athletes and coaches are becoming more and more aware of the advantages of GNSS and other wearable technologies in combination with advanced computer software, paving the way for digital revolution of the science, as well as the practice of sports.

AUTHOR CONTRIBUTIONS

MS, JS, and H-CH contributed to all parts this paper, including the concept, design, and writing. All authors approved the final version for publication.

FUNDING

This project received funding from the European Union's Horizon 2020 research and innovation program under grant agreement no. 824984.

ACKNOWLEDGMENTS

We are thankful to several national ski teams for giving us feedback concerning the performance measurements we have done for them.

REFERENCES

Akenhead, R., French, D., Thompson, K. G., and Hayes, P. R. (2014). The acceleration dependent validity and reliability of 10 Hz GPS. *J. Sci. Med. Sport* 17, 562–566. doi: 10.1016/j.jsams.2013.08.005

Aughey, R. J. (2011). Applications of GPS technologies to field sports. *Int. J. Sports Physiol. Perform.* 6, 295–310. doi: 10.1123/ijspp.6.3.295

Barbero-Alvarez, J. C., Coutts, A., Granda, J., Barbero-Alvarez, V., and Castagna, C. (2010). The validity and reliability of a global positioning satellite system device to assess speed and repeated sprint ability (RSA) in athletes. *J. Sci. Med. Sport* 13, 232–235. doi: 10.1016/j.jsams.2009.02.005

Brodie, M., Walmsley, A., and Page, W. (2008a). Fusion motion capture: a prototype system using inertial measurement units and GPS for the biomechanical analysis of ski racing. *Sports Technol.* 1, 17–28. doi: 10.1080/19346182.2008.9648447

Brodie, M., Walmsley, A., and Page, W. (2008b). "Fusion motion capture: can technology be used to optimise alpine ski racing technique?" in *Impact of Technology on Sports II*, eds S. Ujihashi and A. Subic (London: Taylor & Francis), 825–831.

Coutts, A. J., and Duffield, R. (2010). Validity and reliability of GPS devices for measuring movement demands of team sports. *J. Sci. Med. Sport* 13, 133–135. doi: 10.1016/j.jsams.2008.09.015

Duffield, R., Reid, M., Baker, J., and Spratford, W. (2010). Accuracy and reliability of GPS devices for measurement of movement patterns in confined spaces for court-based sports. *J. Sci. Med. Sport* 13, 523–525. doi: 10.1016/j.jsams.2009.07.003

Fasel, B., Gilgien, M., Sporri, J., and Aminian, K. (2018). A new training assessment method for alpine ski racing: estimating center of mass trajectory by fusing inertial sensors with periodically available position anchor points. *Front. Physiol.* 9:1203. doi: 10.3389/fphys.2018.01203

Fasel, B., Spörri, J., Gilgien, M., Boffi, G., Chardonnens, J., Müller, E., et al. (2016). Three-dimensional body and centre of mass kinematics in alpine ski racing using differential GNSS and inertial sensors. *Remote Sens.* 8:671. doi: 10.3390/rs8080671

Federolf, P., Scheiber, P., Rauscher, E., Schwameder, H., Lüthi, A., Rhyner, H. U., et al. (2008). Impact of skier actions on the gliding times in alpine skiing. *Scand. J. Med. Sci. Sports* 18, 790–797. doi: 10.1111/j.1600-0838.2007.00745.x

Federolf, P. A. (2012). Quantifying instantaneous performance in alpine ski racing. *J. Sports Sci.* 30, 1063–1068. doi: 10.1080/02640414.2012.690073

FIS (2016). *International Ski Competition.* Available online at: https://assets.fis-ski.com/image/upload/v1536838570/fis-prod/assets/2016_ICR_Cancun.pdf (accessed November 14, 2016).

GalileoGNSS (2018). *The Path to High GNSS Accuracy*. Available online at: https://galileognss.eu/the-path-to-high-gnss-accuracy/ (accessed September 3, 2019).

Gilgien, M., Crivelli, P., Spörri, J., Kröll, J., and Müller, E. (2015a). Characterization of course and terrain and their effect on skier speed in world cup alpine ski racing. *PLoS ONE* 10:e0118119. doi: 10.1371/journal.pone.0118119

Gilgien, M., Kröll, J., Spörri, J., Crivelli, P., and Müller, E. (2018). Application of dGNSS in alpine ski racing: basis for evaluating physical demands and safety. *Front. Physiol.* 9:145. doi: 10.3389/fphys.2018.00145

Gilgien, M., Spörri, J., Chardonnens, J., Kröll, J., Limpach, P., and Müller, E. (2015b). Determination of the centre of mass kinematics in alpine skiing using differential global navigation satellite systems. *J. Sport Sci.* 33, 960–969. doi: 10.1080/02640414.2014.977934

Gilgien, M., Spörri, J., Chardonnens, J., Kröll, J., and Müller, E. (2013). Determination of external forces in alpine skiing using a differential global navigation satellite system. *Sensors* 13, 9821–9835. doi: 10.3390/s130809821

Gilgien, M., Spörri, J., Kröll, J., Crivelli, P., and Müller, E. (2014a). Mechanics of turning and jumping and skier speed are associated with injury risk in men's world cup alpine skiing: a comparison between the competition disciplines. *Br. J. Sports Med.* 48, 742–747. doi: 10.1136/bjsports-2013-092994

Gilgien, M., Spörri, J., Kröll, J., and Müller, E. (2016). Effect of ski geometry and standing height on kinetic energy: equipment designed to reduce risk of severe traumatic injuries in alpine downhill ski racing. *Br. J. Sports Med.* 50, 8–13. doi: 10.1136/bjsports-2015-095465

Gilgien, M., Spörri, J., Limpach, P., Geiger, A., and Müller, E. (2014b). The effect of different global navigation satellite system methods on positioning accuracy in elite alpine skiing. *Sensors* 14, 18433–18453. doi: 10.3390/s141018433

Haugen, T., and Buchheit, M. (2016). Sprint running performance monitoring: methodological and practical considerations. *Sports Med.* 46, 641–656. doi: 10.1007/s40279-015-0446-0

Hébert-Losier, K., Supej, M., and Holmberg, H. C. (2014). Biomechanical factors influencing the performance of elite alpine ski racers. *Sports Med.* 44, 519–533. doi: 10.1007/s40279-013-0132-z

Heikenfeld, J., Jajack, A., Rogers, J., Gutruf, P., Tian, L., Pan, T., et al. (2018). Wearable sensors: modalities, challenges, and prospects. *Lab Chip* 18, 217–248. doi: 10.1039/C7LC00914C

Hoppe, M. W., Baumgart, C., Polglaze, T., and Freiwald, J. (2018). Validity and reliability of GPS and LPS for measuring distances covered and sprint mechanical properties in team sports. *PLoS ONE* 13:e0192708. doi: 10.1371/journal.pone.0192708

Jennings, D., Cormack, S., Coutts, A. J., Boyd, L., and Aughey, R. J. (2010). The validity and reliability of GPS units for measuring distance in team sport specific running patterns. *Int. J. Sports Physiol. Perform.* 5, 328–341. doi: 10.1123/ijspp.5.3.328

Johnston, R. J., Watsford, M. L., Kelly, S. J., Pine, M. J., and Spurrs, R. W. (2014). Validity and interunit reliability of 10 Hz and 15 Hz GPS units for assessing athlete movement demands. *J. Str. Cond. Res.* 28, 1649–1655. doi: 10.1519/JSC.0000000000000323

Johnston, R. J., Watsford, M. L., Pine, M. J., Spurrs, R. W., Murphy, A. J., and Pruyn, E. C. (2012). The validity and reliability of 5-Hz global positioning system units to measure team sport movement demands. *J. Str. Cond. Res.* 26, 758–765. doi: 10.1519/JSC.0b013e318225f161

Kröll, J., Spörri, J., Gilgien, M., Schwameder, H., and Müller, E. (2016). Sidecut radius and kinetic energy: equipment designed to reduce risk of severe traumatic knee injuries in alpine giant slalom ski racing. *Br. J. Sports Med.* 50, 26–31. doi: 10.1136/bjsports-2015-095463

Krüger, A., and Edelmann-Nusser, J. (2010). Application of a full body inertial measurement system in alpine skiing: a comparison with an optical video based system. *J. Appl. Biomech.* 26, 516–521. doi: 10.1123/jab.26.4.516

Luethi, S. M., and Denoth, J. (1987). The influence of aerodynamic and anthropometric factors on speed in skiing. *Int. J. Sport Biomech.* 3, 345–352. doi: 10.1123/ijsb.3.4.345

Meyer, F., Le Pelley, D., and Borrani, F. (2012). Aerodynamic drag modeling of alpine skiers performing giant slalom turns. *Med. Sci. Sports Exerc.* 44, 1109–1115. doi: 10.1249/MSS.0b013e3182443315

Nagahara, R., Botter, A., Rejc, E., Koido, M., Shimizu, T., Samozino, P., et al. (2017). Concurrent validity of GPS for deriving mechanical properties of sprint acceleration. *Int. J. Sports Physiol. Perform.* 12, 129–132. doi: 10.1123/ijspp.2015-0566

Nemec, B., Petric, T., Babic, J., and Supej, M. (2014). Estimation of alpine skier posture using machine learning techniques. *Sensors* 14, 18898–18914. doi: 10.3390/s141018898

Parkinson, B. W., and Spilker, J. J. (1996). *Global Positioning System: Theory and Application, Vol. 1*. Washington, DC: American Institute of Aeronautics and Astronautics.

Petersen, C., Pyne, D., Portus, M., and Dawson, B. (2009). Validity and reliability of GPS units to monitor cricket-specific movement patterns. *Int. J. Sports Physiol. Perform.* 4, 381–393. doi: 10.1123/ijspp.4.3.381

Roe, G., Darrall-Jones, J., Black, C., Shaw, W., Till, K., and Jones, B. (2017). Validity of 10-HZ GPS and timing Gates for assessing maximum velocity in professional rugby union players. *Int. J. Sports Physiol. Perform.* 12, 836–839. doi: 10.1123/ijspp.2016-0256

Schutz, Y., and Herren, R. (2000). Assessment of speed of human locomotion using a differential satellite global positioning system. *Med. Sci. Sports Exerc.* 32, 642–646. doi: 10.1097/00005768-200003000-00014

Scott, M. T., Scott, T. J., and Kelly, V. G. (2016). The validity and reliability of global positioning systems in team sport: a brief review. *J. Str. Cond. Res.* 30, 1470–1490. doi: 10.1519/JSC.0000000000001221

Seifriz, F., Mester, J., Krämer, A., and Roth, R. (2003). The use of GPS for continuous measurement of kinematic data and for the validation of a model in alpine skiing. *Int. J. Comp. Sci. Sport* 1, 90–95.

Skaloud, J., and Limpach, P. (2003). "Synergy of CP-DGPS, accelerometry and magnetic sensors for precise trajectography in ski racing," in *Proceedings of the 16th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS/GNSS 2003)* (Portland, OR).

Spörri, J., Kröll, J., Schwameder, H., and Müller, E. (2012). Turn characteristics of a top world class athlete in giant slalom: a case study assessing current performance prediction concepts. *Int. J. Sports Sci. Coach.* 7, 647–659. doi: 10.1260/1747-9541.7.4.647

Spörri, J., Kröll, J., Schwameder, H., and Müller, E. (2018). The role of path length- and speed-related factors for the enhancement of section performance in alpine giant slalom. *Eur. J. Sport Sci.* 18, 911–919. doi: 10.1080/17461391.2018.1453870

Supej, M. (2008). Differential specific mechanical energy as a quality parameter in racing alpine skiing. *J. Appl. Biomech.* 24, 121–129. doi: 10.1123/jab.24.2.121

Supej, M. (2010). 3D measurements of alpine skiing with an inertial sensor motion capture suit and GNSS RTK system. *J. Sports Sci.* 28, 759–769. doi: 10.1080/02640411003716934

Supej, M. (2012). "Gate-to-gate synchronized comparison of velocity retrieved from a high-end global navigation satellite system in alpine skiing," in *28 International Conference on Biomechanics in Sports*, eds A. B. Elizabeth, J. Bradshaw, and A. P. Hume (Melbourne, VIC), 354–357.

Supej, M., and Cernigoj, M. (2006). Relations between different technical and tactical approaches and overall time at men's world cup giant slalom races. *Kinesiol. Slov.* 12, 63–69.

Supej, M., and Cuk, I. (2014). Comparison of global navigation satellite system devices on speed tracking in road (tran)SPORT applications. *Sensors* 14, 23490–23508. doi: 10.3390/s141223490

Supej, M., and Holmberg, H. C. (2011). A new time measurement method using a high-end global navigation satellite system to analyze alpine skiing. *Res. Q. Exerc. Sport* 82, 400–411. doi: 10.1080/02701367.2011.10599772

Supej, M., Kipp, R., and Holmberg, H. C. (2011). Mechanical parameters as predictors of performance in alpine World Cup slalom racing. *Scand. J. Med. Sci. Sports* 21, e72–e81. doi: 10.1111/j.1600-0838.2010.01159.x

Supej, M., Kugovnik, O., and Nemec, B. (2008). "DGPS measurement system in alpine skiing track and center of mass estimation," in *Proceedings of First Joint International Pre-Olympic Conference of Sports Sciences and Sports Engineering, Vol. 1, Computer Science in Sports,* eds Y. Jiang, A. Baca, and H. Zhang (Liverpool: World Academic Union), 120–125.

Supej, M., Sætran, L., Oggiano, L., Ettema, G., Šarabon, N., Nemec, B., et al. (2013). Aerodynamic drag is not the major determinant of performance during giant slalom skiing at the elite level. *Scand. J. Med. Sci. Sports* 23, e38–e47. doi: 10.1111/sms.12007

Townshend, A. D., Worringham, C. J., and Stewart, I. B. (2008). Assessment of speed and position during human locomotion using nondifferential GPS. *Med. Sci. Sports Exerc.* 40, 124–132. doi: 10.1249/mss.0b013e3181590bc2

Varley, M. C., Fairweather, I. H., and Aughey, R. J. (2012). Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *J. Sports Sci.* 30, 121–127. doi: 10.1080/02640414.2011.627941

Varley, M. C., Gabbett, T., and Aughey, R. J. (2014). Activity profiles of professional soccer, rugby league and Australian football match play. *J. Sports Sci.* 32, 1858–1866. doi: 10.1080/02640414.2013.823227

von Hertzen, R., Holmlund, U., and Ranta, M. A. (1997). On the velocity maximization in downhill skiing. *J. Biomech.* 30, 525–529. doi: 10.1016/S0021-9290(96)00167-4

Waegli, A., Skaloud, J., Ducret, S., Skaloud, J., and Pesty, R. (2009). "Assessment of timing and performance based on trajectories from low-cost GPS/INS satellite positioning," in *Science and Skiing IV,* eds E. Müller, S. Lindinger, and T. Stöggl (Maidenhead: Meyer & Meyer Sport (UK) Ltd), 556–564.

Waldron, M., Worsfold, P., Twist, C., and Lamb, K. (2011). Concurrent validity and test-retest reliability of a global positioning system (GPS) and timing gates to assess sprint performance variables. *J. Sports Sci.* 29, 1613–1619. doi: 10.1080/02640414.2011.608703

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.

frontiers in Sports and Active Living

ORIGINAL RESEARCH
published: 23 January 2020
doi: 10.3389/fspor.2020.00002

Comparison of the Turn Switch Time Points Measured by Portable Force Platforms and Pressure Insoles

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Several methods to determine turn switch points during alpine skiing using the vertical GRF exist in the literature. Although comparative studies between pressure insoles (PI) and force platforms (FP) have been conducted, there are no reports comparing the detected time points. Yet, these sensors and methods have been used interchangeably. This study aims to compare the turn switch time points with both sensors and various methods. Twenty skiers performed turns with FP and PI for two different ski styles (high and low dynamic turns). Three different assessment methodologies were compared: minima, functional minima, and crossings. Bland Altman and repeated measures ANOVA were used to assess statistical differences. Main effects of sensor and method were observed ($p < 0.001$). Although there was a low effect size ($\eta_p^2 = 0.013$) between FP and PI, the 95% CI yielded values representing >30% of the turn duration. A large effect size ($\eta^2 = 0.153$) was found between the crossing method and the minima and functional minima methods. This indicates that those methods assess different events during the turn switch phase. In conclusion, the sensors and assessment methodologies compared in this study are not interchangeable with the possible exception of the minima and functional minima assessed with FP.

Keywords: event detection, force binding, GRF, pressure, sensor, ski

OPEN ACCESS

Edited by:
Laura Gastaldi,
Politecnico di Torino, Italy

Reviewed by:
Marko S. Laaksonen,
Mid Sweden University, Sweden
Pietro Picerno,
University of eCampus, Italy

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Specialty section:
This article was submitted to Sports Science, Technology and Engineering, a section of the journal Frontiers in Sports and Active Living

Received: *30 October 2019*
Accepted: *06 January 2020*
Published: *23 January 2020*

Citation:
Martínez A, Nakazato K, Scheiber P, Snyder C and Stöggl T (2020) Comparison of the Turn Switch Time Points Measured by Portable Force Platforms and Pressure Insoles. Front. Sports Act. Living 2:2. doi: 10.3389/fspor.2020.00002

INTRODUCTION

In sports, the determination of performance usually depends on small details. Consequently, qualitative assessment of the factors influencing performance is necessary for both recreational and elite levels. The characteristics of alpine skiing make it challenging to study the different features related to performance, injuries, or coaching. Over the last decades there have been several studies using sensors that could collect data while skiing (Müller et al., 1998; Supej et al., 2008; Stricker et al., 2010; Supej, 2010; Nakazato et al., 2011; Hirose et al., 2013; Nemec et al., 2014; Falda-Buscaiot and Hintzy, 2015). To properly assess the specific details influencing alpine skiing such as edge angle, symmetry or turn phases (Müller and Schwameder, 2003; Spörri et al., 2012; Supej et al., 2013; Hebert-Losier et al., 2014), it is necessary to segment the ski runs into the basic units, ski turns. In order to calculate those metrics, it is essential to determine precisely when each turn begins (Spörri et al., 2012).

The typical motion during alpine skiing consists on a cyclic loading and unloading phase for each turn. The up-unweighting phase is characterized by a load shift from the outer to the inner ski (Müller and Schwameder, 2003). This shift is suggested to correspond with the moment of edge change, and consequently the turn switch point (Nakazato et al., 2011).

Accordingly, the ground reaction force (GRF) is frequently used to determine turn switches (Nakazato et al., 2011; Spörri et al., 2015; Yu et al., 2016). Two sensors have been used indiscriminately to measure GRF: portable force platforms (FP), and pressure insoles (PI). Although FP are the gold standard for force measurement, PI presents some advantages facilitating the data collection process. PI are generally easy to use, wireless, almost non-obtrusive, while FP require extra mechanics, wiring and energy supply. Differences have been found between the force values measured with both sensors during skiing (Nakazato et al., 2011). The PI tend to underestimate the force values from 21 to 54% depending on the phase of the turn, the skier's level, the slope, and the skiing style (Nakazato et al., 2011). Additionally, the force application point and the center of pressure have been shown to follow different patterns, accentuated in the mediolateral direction (Nakazato et al., 2013). These differences are likely due to the sensor locations, as plantar pressure systems do not measure a significant component of the GRF that is transferred through the ski boot cuff (Stricker et al., 2010; Nakazato et al., 2011). Although comparisons between FP and PI have been done regarding force magnitude and application point, to the authors knowledge there are no studies comparing the time point of the turn switch based on GRF measures.

Apart from the various sensors, several methods to assess the turn switch point based on GRF have been used. Nakazato et al. (2011) used the minimum value of the vertical GRF, representing the point with the minimum load. Although data was collected from both FP and PI, the determination of the turn switch point was only based on the total force combined from both legs assessed with FP. Spörri et al. (2015) detected the beginning and end of each turn based on what they called the "functional minima" of the GRF during the turn switch. To calculate the functional minima, they selected the force values below a certain threshold for each run. The threshold was set as the highest minima among all the summed left and right turn force curves. They defined the turn switch point as the midpoint between the first and the last time points of each turn below this threshold. The advantage of this assessment methodology is that it avoids possible misdetections of turn switch points due to noise or vibrations. Finally, between turns there is a load transmission from the outside to the inside leg. During this phase, there is a point where the load is equal for both sides. It has been suggested that this point could correspond with the turn switch point (Müller and Schwameder, 2003; Yu et al., 2016).

In order to determine if the FP and PI measurement systems can be used interchangeably for turn detection in alpine skiing, this study aims to compare the time points of turn detection between FP and PI using the different methodologies previously proposed. A second aim is to compare those turn detection methodologies and evaluate if they detect the same events during alpine skiing.

MATERIALS AND METHODS

To assess the agreement of the turn switch point detection between various assessment methodologies measured with FP and PI, a study was designed where skiers performed alpine skiing turns in two styles (high and low dynamic turns).

Participants

A total of 20 skiers (18 males and 2 females; Mean ± SD: Age = 24.7 ± 3.5 years; Height = 1.78 ± 0.08 m; Weight = 73.7 ± 9.2 kg) took part in the study. Before the measurement, all participants were informed in detail about the testing procedures, as well as possible benefits and risks of the investigation prior to signing the consent form approved by the local Ethics Committee. The experiment was conducted in accordance with the Declaration of Helsinki.

The measurements were performed for 10 days within 2 weeks. The snow temperature was consistent across all measurement days with a mean temperature of −1.1 ± 2.2°C. The mean air temperature was −0.4 ± 4.8°C. The upper part of the measurement slope had an inclination of 23° while the bottom part had an inclination of 15°. The slope was machine groomed daily resulting in a compact layer of natural and artificial snow.

Two different skiing styles were performed. The skiing technique "Carving in Short Radii" (Wörndle et al., 2011) (which is characterized by a short radius turn and dynamic vertical movement) was defined as high dynamic turns. The technique "Parallel Ski Steering in Long Radii" (Wörndle et al., 2011) (which is characterized by a long radius skidded turn and less dynamic movement) was defined as low dynamic turns. Two different courses were set. While the vertical distance between gates was kept constant for both techniques (between 14 and 17 m depending on the inclination), the corridors were 5 and 10 m for the high dynamic and the low dynamic turns, respectively. Short poles were set into the slope as gates. After a warm up run, each skier performed one run per skiing style in a randomized order. Each run consisted in 20 double turns.

Equipment

Two different skis were utilized. To properly select the skis, the participants level were assessed based on the Austrian ski teaching concept (Wörndle et al., 2011) by an accredited instructor. The skiers classified as intermediate ($n = 10$) used recreational skis (length = 169 cm, radius = 15 m) and the skiers classified as experts ($n = 10$) used racing skis (length = 184 cm, radius = 23 m). Regardless of the assessed level, all skiers were able to properly perform the required ski styles. The skiers used their own ski boots. The skis were equipped with a portable FP system and a pair of PI were placed inside the liners (**Figure 1**).

Sensors

The FP system consisted of four dynamometers (Kistler, Winterthur, Switzerland) mounted under the toe and heel binding of each ski. Each dynamometer weighed 0.9 kg, was 36 mm high, and consisted of a top and bottom plate connected by three three-dimensional piezoelectric force transducers. Amplifiers, power supply, supply box, and data loggers (4 kg) were carried in a backpack worn by the skiers (see detailed description; Stricker et al., 2010). The PI (Pedar, Novel, Munich, Germany) were formed by 99 cells, each of them including one

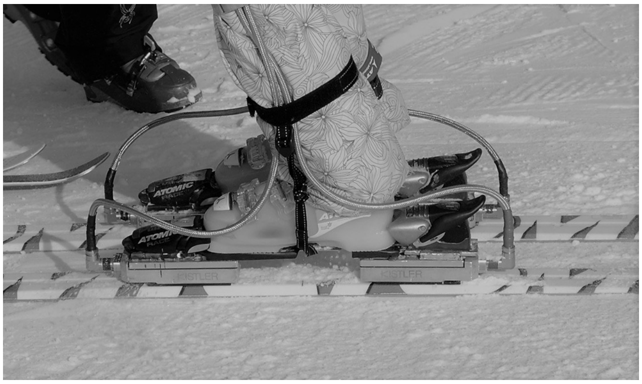

FIGURE 1 | Set up of the FP between the bindings and the skis.

capacitive sensor. The PI were located inside the liners of the ski boots and the proper size was selected for each skier and replaced their normal insoles. All pressure insoles were calibrated prior to the measurements following the manufacturer's instructions. The Novel data logger, battery pack, and trigger switch were carried in a belt (1 kg in total) attached to the Kistler backpack.

Both systems recorded at 100 Hz, which represents the maximum sampling rate of the PI. In order to synchronize the two systems, participants were asked to stomp at the beginning and end of every run.

Data Analysis

In the current study, three turn detection methodologies were applied to the data collected simultaneously with both measurement systems (FP and PI). Prior to the application of the turn detection methodologies, the data sets where synchronized (based on GRF peaks produced by the stomps). The force values of the PI are the sum of the force from each cell, which is obtained multiplying its pressure by its area.

The three different turn switch methods assessed were (**Figure 2**):

1. *GRF minima.* This method uses the minimum value of the vertical component of the GRF determined by the sum of forces from both legs (Nakazato et al., 2011).
2. *GRF functional minima.* This method approximates the point of the minimum value of the GRF summed from both legs based on the cyclic loading and unloading pattern. It avoids possible misdetections of the turn switch point due to noise or vibrations (Spörri et al., 2015, 2016; Kröll et al., 2016).
3. *GRF crossing.* The turn switch point is determined by the point when the magnitudes of GRF of both legs are equal (Müller and Schwameder, 2003; Yu et al., 2016).

In addition, 1, 3, and 6 Hz low pass Butterworth filter frequencies were used and compared. The 3 and 6 Hz filters have been used in previous literature (Spörri et al., 2015, 2016; Martínez et al., 2019), therefore they were selected. The 1 Hz cut-off yielded the lowest bias and range (see section Statistical Analysis) in a pilot study.

Statistical Analysis

Data processing was performed using IkeMaster (Ike Software Solutions, Salzburg, Austria) and Matlab (Version R2018b, The MathWorks Inc., Natick, MA, USA). To assess the interchangeability and agreement between methodologies and sensors, the bias, and limits of agreement were calculated as proposed by Bland and Altman (1986) (Excel 2016, Microsoft, Redmond, WA, USA). The range was set as the difference between the upper and lower limits of agreement, representing the 95% confidence interval (CI). The comparisons between methods and sensors were performed for the three different cut-off filtering options and for the different intensities: high dynamic turns ($N = 1{,}316$), low dynamic turns ($N = 1{,}156$), and for all turns pooled together ($N = 2{,}472$).

A repeated measures analysis of variance (RMANOVA) (SPSS Inc., Version 25.0, Chicago, IL, USA) was used to assess statistical differences with respect to system (FP vs. PI), calculation method (minima vs. functional minima vs. crossing), filter (1 vs. 3 vs. 6 Hz), and ski dynamics (high vs. low dynamic turns). Mauchly's Test of Sphericity indicated that the assumption of sphericity was not met, consequently Greenhouse-Geisser correction was utilized. If significant differences were found, Bonferroni's *post-hoc* test was applied. In order to perform the RMANOVA, a reference value was necessary to compare relative turn switch points (i.e., measured turn switch—reference turn switch). This reference was calculated independently for each turn and cut-off frequency as the mean of the 6 measured turn switch points (two sensors by three methods; **Figure 3**). Eta squared (η^2) and partial eta squared (η_p^2) were used to calculate effect size. Effect sizes were classified as small 0.01–0.06; medium 0.06–0.14, and large >0.14 (Pallant and Manual, 2010). A significance value of $\alpha = 0.05$ was chosen.

RESULTS

The agreement between sensors and methodologies are presented in **Table 1**. Bias and range were consistently lower for the high dynamic turns than for the low dynamic turns in all the conditions assessed, across all systems and methods.

The comparison between FP and PI for all turns pooled together yielded bias lower than 0.05 s and ranges between 1.09 and 1.36 s, except for the "crossing" method with ranges starting at 0.58 s. The "minima" and "functional minima" methods had the highest agreement for both sensor types (FP and PI). Although the comparison between "minima" and "functional minima" methods had the highest agreement for both sensors, the results were not similar. Including all cut-off frequencies, the bias and range were <0.002 and 0.400 s for the FP, but >0.012 and 0.850 s for the PI, respectively. This behavior was consistent, the comparison between assessment methodologies showed systematically lower bias and range values when the FP system was used.

Results for the mean and standard deviation for each assessment option are shown in **Table 2.** No main effects of frequency or intensity were observed. Main effects of sensor were observed between FP and PI ($p < 0.001$), but the effect size was

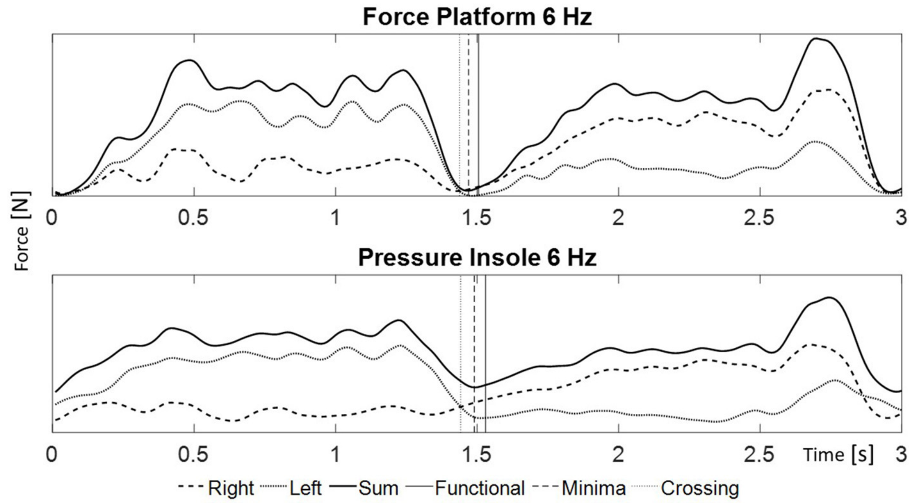

FIGURE 2 | Example of the signals during a turn: the right foot (dashed line), the left foot (dotted line), and the sum (solid line). In the upper graph GRF measured with the FP placed under the bindings. In the lower graph force calculated from the pressure values from the PI between the boot and the foot. The vertical lines represent the turn switch points assessed with the different methods: minima (dashed line), functional minima (solid line) and crossing (dotted line).

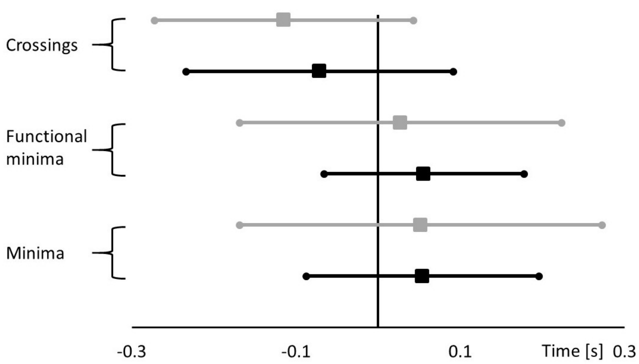

FIGURE 3 | Example of the different moments in time detected by FP (in black) and PI (in gray) represented as the mean ± SD for the 3 different assessing methodologies at 6 Hz with all the turns pooled together.

small ($\eta_p^2 = 0.013$). Main effects of method were also observed ($p < 0.001$) with a large effect size ($\eta_p^2 = 0.427$). *Post-hoc* analysis indicated that all three methods were significantly different than one another. However, while the means of minima and functional minima were statistically different, they were within 0.02 s with a small effect size ($\eta^2 = 0.001$). On the other hand, the differences between both the minima and the functional minima and the crossing method were >0.13 s with a large effect size ($\eta^2 = 0.153$).

The average turn duration for high and low dynamic turns was 1.66 ± 0.27 and 2.55 ± 0.32 s, respectively. The range between FP and PI for the most similar methodologies (minima and functional minima) represents ∼30 and 40% of turn duration for high and low dynamic turns, respectively. The range between minima and functional minima assessed using the PI represents a 33 and 48% of the turn duration for high and low dynamic turns, respectively, and 13% of the turn duration when assessed with the FP, independent of the turn dynamics.

DISCUSSION

The current study focused on the comparison between time points of the turn switch during alpine skiing assessed with different methodologies and using FP and PI. The results showed that all the methods yielded better agreement when the data was collected using the FP than when it was collected using the PI (**Table 1**). This trend was accentuated for highly dynamic turns. The higher consistency found with the FP might be due to the improved transmission of the forces from the legs via the boots to the skis, which might not detected by the PI (Supej et al., 2008). The FPs measure the total forces acting between the skis and the bindings, including the force transferred by the boot cuff. On the other hand, the PIs only measures the transmission of forces from the foot to the boot, which will be only part of the force transmitted to the binding. Due to the movement of the skier and the shift in load distribution during the turn, the fraction of the forces measured by PI compared to FP is not constant during the turn (Nakazato et al., 2011, 2013), and could affect the time points where events are detected.

Main effects of sensor were observed between FP and PI, however the effect size was small (0.013). A possible interpretation of those results is that the large number of turns included in the analysis ($n = 2{,}472$) lead to a type 1 error, were negligible differences are deemed statistically significant. Regardless of the risk of type 1 error, and to the potential misinterpretation of the data, the magnitude of the ranges yielded by the Bland and Altman comparisons show a CI that represents between 30 and 40% of the total turn duration. Consequently, due to the lack of agreement between sensors, these sensors should not be interchanged when comparing turn switch points

TABLE 1 | Bias and range of the 95% CI of the different comparisons between the different assessment methodologies.

			All			Hi			Lo		
			1 Hz	3 Hz	6 Hz	1 Hz	3 Hz	6 Hz	1 Hz	3 Hz	6 Hz
FP vs. PI comparison	Min	Bias	0.009	0.002	0.003	0.032	0.017	0.017	0.056	0.022	0.025
		Range	1.357	1.186	1.229	0.565	0.454	0.526	1.875	1.662	1.704
	Functional	Bias	0.022	0.025	0.029	0.036	0.025	0.023	0.089	0.082	0.087
		Range	1.139	1.090	1.111	0.532	0.502	0.512	1.525	1.470	1.498
	Crossing	Bias	0.015	0.026	0.044	0.010	0.016	0.037	0.020	0.037	0.052
		Range	0.579	0.672	0.789	0.452	0.577	0.684	0.695	0.764	0.893
FP method comparison	Min vs. Functional	Bias	0.002	0.001	0.001	0.002	0.005	0.006	0.001	0.005	0.003
		Range	0.198	0.315	0.391	0.031	0.102	0.211	0.287	0.447	0.525
	Min vs. Crossing	Bias	0.135	0.138	0.126	0.085	0.097	0.076	0.192	0.184	0.182
		Range	0.723	0.736	0.820	0.608	0.660	0.702	0.776	0.775	0.886
	Functional vs. Crossing	Bias	0.137	0.139	0.127	0.087	0.103	0.082	0.193	0.180	0.179
		Range	0.668	0.700	0.778	0.604	0.639	0.673	0.669	0.731	0.837
PI method comparison	Min vs. Functional	Bias	0.012	0.023	0.024	0.007	0.013	0.012	0.032	0.064	0.066
		Range	0.857	0.914	0.933	0.487	0.511	0.550	1.134	1.201	1.212
	Min vs. Crossing	Bias	0.141	0.162	0.167	0.127	0.130	0.130	0.156	0.199	0.209
		Range	1.323	1.237	1.286	0.725	0.696	0.738	1.772	1.638	1.694
	Functional vs. Crossing	Bias	0.129	0.139	0.142	0.133	0.143	0.141	0.124	0.134	0.143
		Range	1.095	1.084	1.112	0.707	0.699	0.701	1.413	1.398	1.444

Values are expressed in seconds. Three different cut-off frequencies are reported: 1, 3, and 6 Hz. Results are classified by: all turns together, high dynamic turns and low dynamic turns. All, all turns pooled together; Hi, high dynamic turns; Lo, low dynamic turns; Min, assessment method previously referred as GRF minima; Functional, assessment method previously referred as GRF functional minima; Crossing, assessment method previously referred as GRF crossing.

TABLE 2 | Mean and SD of the different comparisons between the different assessment methodologies.

			All			Hi			Lo		
			1 Hz	3 Hz	6 Hz	1 Hz	3 Hz	6 Hz	1 Hz	3 Hz	6 Hz
FP	Min	Mean	−0.054	0.055	0.052	−0.023	0.026	0.018	−0.089	0.087	0.092
		SD	0.141	0.131	0.138	0.075	0.067	0.065	0.185	0.173	0.182
	Functional	Mean	−0.055	0.055	0.054	−0.029	0.032	0.020	−0.086	0.082	0.092
		SD	0.122	0.116	0.126	0.064	0.060	0.063	0.159	0.152	0.163
	Crossing	Mean	0.072	−0.083	−0.083	0.053	−0.071	−0.067	0.093	−0.098	−0.101
		SD	0.163	0.148	0.148	0.136	0.126	0.120	0.185	0.167	0.170
PI	Min	Mean	−0.051	0.053	0.043	−0.040	0.043	0.050	−0.064	0.064	0.035
		SD	0.221	0.215	0.242	0.109	0.098	0.114	0.301	0.296	0.332
	Functional	Mean	−0.027	0.030	0.031	−0.052	0.057	0.057	0.001	0.000	0.003
		SD	0.196	0.194	0.191	0.103	0.103	0.107	0.262	0.258	0.253
	Crossing	Mean	0.115	−0.109	−0.098	0.090	−0.087	−0.077	0.145	−0.135	−0.121
		SD	0.158	0.145	0.140	0.117	0.111	0.100	0.189	0.173	0.172

Values are expressed in seconds. Results are classified by: all turns together, high dynamic turns and low dynamic turns. All, all turns pooled together; Hi, high dynamic turns; Lo, low dynamic turns; Min, assessment method previously referred as GRF minima; Functional, assessment method previously referred as GRF functional minima; Crossing, assessment method previously referred as GRF crossing; SD, standard deviation.

or metrics measured turn by turn as the cutting point will affect the calculations (Spörri et al., 2012).

The same discussion is relevant for the comparison between the methods. Although there is a main effect of methodology, with a large effect size (0.427), the differences are mostly with respect to the crossings method (>0.13 s; $\eta^2 > 0.153$) and not between the minima and functional minima (<0.02 s; $\eta^2 = 0.001$). Nevertheless, the ranges between minima and functional minima assessed with PI represents >30% of the turn duration which leads to the conclusion that they are not interchangeable. On the other hand, when using the FP, the range represents a 13% of the turn duration, which depending on the aim of the turn detection, could allow for the use of both the minima and functional minima methods interchangeably from FP measurements.

The results indicate that the crossings methodology assesses different events or points in time than the other two methods. Furthermore, the bias and range for this method are considerably higher than the bias and range of the minima to functional minima comparison. A possible explanation for this is that the minima and functional minima methods represent two approaches to the same concept, where the turn switch point corresponds with the point of minimum load from both legs (Müller et al., 1998; Spörri et al., 2015). Consequently, these methods, though different, are more similar to each other than the crossing method. For this method, the point when the load is equal between both legs is used (Müller and Schwameder, 2003). Although both events need to happen during the turn switch phase, they do not necessarily represent the same point in time within the turn switch phase.

Regardless of the apparent similarities in performance between sensors and methods, the results suggest that they are not entirely interchangeable. Although bias' are generally small and suggest that both sensors are assessing the same event, the high ranges (>30% of the turn) highlight the differences of the points actually detected. Unfortunately, we cannot determine which sensor or method would be most representative of the true turn switch point due to the lack of valid reference data, both in the literature and this study. Based on the results, the methodology based on the minima seems to be the most appropriate to apply in the field. It presents the lowest bias values between the two sensors and also the smallest range for highly dynamic turns. On the other hand, both sensors present some advantages and disadvantages. FP showed consistently better results, yet the use of FP in training is not a feasible option. It changes the height of the bindings, adds weight to the skis and implies more weight and wires in the skier's body. For this reason, the implementation of a less cumbersome pressure sensor outside of the boot could potentially solve the problem of the missing forces through the boot cuff and provide reliable data similar to the FP. A future study using a gold standard methodology for the location of the turn switch point needs to be defined and consequently compared with the various methodologies applied for detecting the turn switch.

CONCLUSIONS

The aim of the study was to assess if sensors (FP and PI) or assessment methods (minima, functional minima, and crossings) could be used interchangeably, and according to the results of this study, they are not. The only exception being the minima and functional minima methods assessed with FP. The results of the study also suggest that the use of the FP sensor to determine turn switches based on GRF is recommended. Further research is needed to evaluate the precision of the different systems and determine which assessment method is most correlated with the real turn switch point.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the University of Salzburg. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AM and TS: conceptualization and formal analysis. AM, KN, PS, and TS: methodology. AM: software and visualization. AM, CS, and TS: investigation. TS: resources, supervision, and funding acquisition. PS: data curation. AM: writing—original draft preparation. TS, CS, PS, and KN: writing—review and editing.

FUNDING

No funding was received for this work from the National Institutes of Health, the Welcome Trust, the Howard Hughes Medical Institute, or other funding agencies to PubMed Central. Funding was provided based on the two Salzburg Trans-4-Tech projects Ski Sense and Sport Sense and by the Austrian Ministry for Transport, Innovation and Technology, the Federal Ministry for Digital and Economic Affairs, and the federal state of Salzburg under the research programme COMET—Competence Centers for Excellent Technologies—in the project Digital Motion in Sports, Fitness, and Well-being (DiMo).

ACKNOWLEDGMENTS

The authors would like to thank Stephanie Moore for the valuable discussions about the project.

REFERENCES

Bland, J. M., and Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1, 307–310. doi: 10.1016/S0140-6736(86)90837-8

Falda-Buscaiot, T., and Hintzy, F. (2015). Comparison of muscle activation pattern between alpine skiing and snowboarding. *Comput. Methods Biomech. Biomed. Eng.* 18(Suppl. 1), 1936–1937. doi: 10.1080/10255842.2015.1069576

Hebert-Losier, K., Supej, M., and Holmberg, H. C. (2014). Biomechanical factors influencing the performance of elite alpine ski racers. *Sports Med.* 44, 519–533. doi: 10.1007/s40279-013-0132-z

Hirose, K., Doki, H., and Kondo, A. (2013). Dynamic analysis and motion measurement of ski turns using inertial and force sensors. *Proc. Eng.* 60, 355–360. doi: 10.1016/j.proeng.2013.07.082

Kröll, J., Spörri, J., Gilgien, M., Schwameder, H., and Müller, E. (2016). Effect of ski geometry on aggressive ski behaviour and visual aesthetics: equipment designed to reduce risk of severe traumatic knee injuries in alpine giant slalom ski racing. *Br. J. Sports Med.* 50, 20–25. doi: 10.1136/bjsports-2015-095433

Martínez, A., Jahnel, R., Buchecker, M., Snyder, C., Brunauer, R., and Stöggl, T. (2019). Development of an automatic alpine skiing turn detection algorithm based on a simple sensor setup. *Sensors* 19:902. doi: 10.3390/s19040902

Müller, E., Bartlett, R., Raschner, C., Schwameder, H., Benko-Bernwick, U., and Lindinger, S. (1998). Comparisons of the ski turn techniques of experienced and intermediate skiers. *J. Sports Sci.* 16, 545–559. doi: 10.1080/026404198366515

Müller, E., and Schwameder, H. (2003). Biomechanical aspects of new techniques in alpine skiing and ski-jumping. *J. Sports Sci.* 21, 679–692. doi: 10.1080/0264041031000140284

Nakazato, K., Scheiber, P., and Müller, E. (2011). A comparison of ground reaction forces determined by portable force-plate and pressure-insole systems in alpine skiing. *J. Sports Sci. Med.* 10, 754–762.

Nakazato, K., Scheiber, P., and Müller, E. (2013). Comparison between the force application point determined by portable force plate system and the center of pressure determined by pressure insole system during alpine skiing. *Sports Eng.* 16, 297–307. doi: 10.1007/s12283-013-0119-x

Nemec, B., Petric, T., Babic, J., and Supej, M. (2014). Estimation of alpine skier posture using machine learning techniques. *Sensors* 14, 18898–18914. doi: 10.3390/s141018898

Pallant, J., and Manual, S. S. (2010). *A Step by Step Guide to Data Analysis Using SPSS*. Berkshire: McGraw-Hill Education.

Spörri, J., Kröll, J., Fasel, B., Aminian, K., and Müller, E. (2016). Course setting as a prevention measure for overuse injuries of the back in alpine ski racing: a kinematic and kinetic study of giant slalom and slalom. *Orthopaed. J. Sports Med.* 4:2325967116630719. doi: 10.1177/2325967116630719

Spörri, J., Kröll, J., Haid, C., Fasel, B., and Müller, E. (2015). Potential mechanisms leading to overuse injuries of the back in alpine ski racing: a descriptive biomechanical study. *Am. J. Sports Med.* 43, 2042–2048. doi: 10.1177/0363546515588178

Spörri, J., Kröll, J., Schwameder, H., and Müller, E. (2012). Turn characteristics of a top world class athlete in giant slalom: a case study assessing current performance prediction concepts. *Int. J. Sports Sci. Coach.* 7, 647–659. doi: 10.1260/1747-9541.7.4.647

Stricker, G., Scheiber, P., Lindenhofer, E., and Müller, E. (2010). Determination of forces in alpine skiing and snowboarding: validation of a mobile data acquisition system. *Eur. J. Sport Sci.* 10, 31–41. doi: 10.1080/17461390903108141

Supej, M. (2010). 3D measurements of alpine skiing with an inertial sensor motion capture suit and GNSS RTK system. *J. Sports Sci.* 28, 759–769. doi: 10.1080/02640411003716934

Supej, M., Kugovnik, O., and Nemec, B. (2008). "DGPS measurement system in alpine skiing track and center of mass estimation," in *Proceedings of First Joint International Pre-Olympic Conference of Sports Sciences and Sports Engineering* (Nanjing), 120–125.

Supej, M., Sætran, L., Oggiano, L., Ettema, G., Šarabon, N., Nemec, B., et al. (2013). Aerodynamic drag is not the major determinant of performance during giant slalom skiing at the elite level. *Scand. J. Med. Sci. Sports* 23, e38–e47. doi: 10.1111/sms.12007

Wörndle, W., Jenny, F., and Furtner, M. (2011). *Snowsport Austria, die Österreichischen Skischlen.* Alpiner Skilauf (Alpine skiing). Die Österreichischer Skischulverband.

Yu, G., Jang, Y. J., Kim, J., Kim, J. H., Kim, H. Y., Kim, K., et al. (2016). Potential of IMU sensors in performance analysis of professional alpine skiers. *Sensors* 16:463. doi: 10.3390/s16040463

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.

frontiers in Sports and Active Living

METHODS
published: 03 March 2020
doi: 10.3389/fspor.2020.00012

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Monitoring the Return to Sport Transition After ACL Injury: An Alpine Ski Racing Case Study

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Alpine ski racing is an extreme sport and ski racers are at high risk for ACL injury. ACL injury impairs neuromuscular function and psychological readiness putting alpine skiers with ACL injury at high risk for ACL reinjury. Consequently, return to sport training and testing protocols are recommended to safeguard ACL injured athletes against reinjury. The aim of this paper was to present a real-world example of a return to sport training plan for a female elite alpine ski racer who sustained an ACL injury that was supported by an interdisciplinary performance team (IPT) alongside neuromuscular testing and athlete monitoring. A multi-faceted return to sport training plan was developed by the IPT shortly after the injury event that accounted for the logistics, healing, psychological readiness, functional milestones, work capacity and progression to support the return to sport/return to performance transition. Neuromuscular testing was conducted at several timepoints post-injury. Importantly, numerous pre-injury tests provided a baseline for comparison throughout the recovery process. Movement competencies and neuromuscular function were assessed, including an evaluation of muscle properties (e.g., the force-velocity and force-length relationships) to assist the IPT in pinpointing trainable deficits and managing the complexities of the return to sport transition. While the athlete returned to snow 7 months post-injury, presenting with interlimb asymmetries below 10%, functional and strength deficits persisted up to 18 months post-injury. More research is required to establish a valid return to sport protocol for alpine ski racers with ACL injury to safeguard against the high risk for ACL reinjury.

Keywords: knee injuries, training load, vertical jump asymmetry, vertical jump power, quadriceps/hamstrings strength, ACL reinjury

OPEN ACCESS

Edited by:
Jörg Spörri, Balgrist University Hospital, Switzerland

Reviewed by:
Zimi Sawacha, University of Padova, Italy
Nathan D. Schilaty, Mayo Clinic, United States

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Specialty section:
This article was submitted to Sports Science, Technology and Engineering, a section of the journal Frontiers in Sports and Active Living

Received: *10 September 2019*
Accepted: *28 January 2020*
Published: *03 March 2020*

Citation:
Jordan MJ, Morris N, Lane M, Barnert J, MacGregor K, Heard M, Robinson S and Herzog W (2020) Monitoring the Return to Sport Transition After ACL Injury: An Alpine Ski Racing Case Study. Front. Sports Act. Living 2:12. doi: 10.3389/fspor.2020.00012

INTRODUCTION

An anterior cruciate ligament (ACL) tear is the most common injury amongst alpine ski racers (Flørenes et al., 2009; Bere et al., 2014), and the injury rate has remained high despite injury prevention efforts (Haaland et al., 2016). ACL reconstruction (ACLR) surgery is often recommended to alpine skiers who have sustained an ACL injury to restore knee joint stability (Jordan et al., 2017a). However, ≈20–30% of alpine ski racers with ACLR will subsequently suffer an ACL reinjury, often to the contralateral limb and within 2 years post-surgery (Pujol et al., 2007; Haida et al., 2016; Jordan et al., 2017c). ACL tears in alpine ski racing are typically severe and occur alongside combined injury to other knee joint structures (e.g., multi-ligament injury, articular cartilage injury, meniscal tears), which may accelerate the development of early onset knee joint osteoarthritis (Jordan et al., 2017c).

It is estimated that between 50 and 60% of athletes who sustain an ACL injury will return to competitive sport (Ardern et al., 2014; Webster et al., 2019), while the proportion of alpine skiers returning to competitive sport may be even higher (Haida et al., 2016). Athletes who undergo ACLR surgery require extensive rehabilitation and training to restore knee joint function and objectively determined functional criteria are recommended to guide the return to sport transition to safeguard against secondary ACL injury (Buckthorpe, 2019). However, sports medicine practitioners and trainers often rely solely on time-based criteria to determine when an athlete is sufficiently prepared to return to sport (Barber-Westin and Noyes, 2011), and it has been shown that only a small fraction of ACLR athletes (23%) pass objectively determined functional criteria prior to return to sport (Webster and Hewett, 2019).

Further, passing commonly conducted return to sport testing batteries that include criteria like achieving >90% limb symmetry in single leg hop tests, appear to provide little assurance that an athlete is physically prepared for return to sport after ACLR to avoid a second ACL injury (Webster and Hewett, 2019). A prospective study evaluating a battery of return to sport tests after ACLR found no association between achieving a limb symmetry index >90% in various functional tests, such as the single leg hop for distance, single leg triple hop, and 6 m timed hop, and a reduction in ACL reinjury rates (Grindem et al., 2016). Only quadriceps strength symmetry, and delaying return to sport in the first 9 months post-surgery, were associated with a reduction in the risk for ACL reinjury. These findings suggest that ACLR athletes may compensate in return to sport functional tests to achieve the established benchmark while potentially masking deficits that put them at risk for ACL reinjury.

In addition to the prevalence of ACL reinjury (Pujol et al., 2007; Haida et al., 2016; Jordan et al., 2017a), actively competing alpine skiers with ACLR have also been shown to demonstrate functional deficits compared to non-injured alpine ski racers, including elevated interlimb asymmetry in lower limb muscle power, thigh muscle rapid force development ability (rate of force development—RFD), and thigh muscle maximal strength that persist despite returning to competitive sport (Jordan et al., 2015b,c, 2017b, 2018). The high frequency of ACL injury in alpine ski racing, the likelihood for combined injury, and the fact that many alpine skiers will attempt to return to sport after ACLR surgery, strongly suggest the importance of a sport-specific return to sport protocol to safeguard alpine skiers against ACL reinjury (Jordan et al., 2015a). Further, building resilience against ACL reinjury is multifactorial and involves not only restoring functional abilities and tissue healing but also psycho-emotional readiness (Ardern et al., 2011). Therefore, athletes returning from ACL injury may be best supported by an interdisciplinary performance team (IPT) in which domain-specific practitioners work collaboratively to support the transition back to sport (Forsdyke et al., 2017; Wang et al., 2019).

The aim of this case study is to present the details of a return to sport training and testing protocol used with a female elite alpine ski racer who sustained an ACL injury and subsequently underwent ACLR surgery. The return to sport transition presented in this case study will include discussion on the importance of objective functional assessments, workload monitoring, the restoration of work capacity and the role of the IPT in supporting alpine skiers with ACLR throughout the return to sport and return to performance transition.

RETURN TO SPORT TESTING METHODOLOGY

Participant Characteristics

A female elite alpine ski racer (Age = 28 years) sustained a right knee injury (high grade ACL tear, medial meniscal tear, lateral tibial plateau compression fracture). She underwent an ACLR surgery using an 8.5 mm quadruple semitendinosus (ST) autograft. The Conjoint Research Ethics Board at the University of Calgary approved the experimental protocols and the participant gave written informed consent prior to her involvement in the testing protocols.

Interdisciplinary Performance Team Personnel and Testing Environment

The athlete's IPT consisted of seven sport science/sport medicine practitioners including the following disciplines: sport science/physiology, strength & conditioning (S&C), physiotherapy, sports medicine, orthopedic surgery, mental performance, and sport nutrition/dietetics. All neuromuscular testing was undertaken in the Strength and Power laboratory at the Canadian Sport Institute Calgary by qualified exercise testing personnel. A return to sport training plan detailed the athlete's training/rehabilitation priorities and logistics supporting the rehabilitation/re-training process.

Internal Workload Monitoring

Internal workload was assessed using the sessional rating of perceived exertion (sRPE) method (Foster, 1998). The participant was asked to record the training session type, the training session duration in minutes and the perceived exercise intensity using a modified Borg scale (1 = Easy, 10 = Maximal) for every unique training session each day. Data was collected using an online form. The session duration in minutes and perceived session intensity were multiplied to obtain the internal sessional workload in arbitrary units (AU). The weekly internal training load was then obtained by summing the sRPE workload for the total number of training sessions per week (total number of training weeks recorded from May 2012 to May 2019: n = 315). Logging compliance was not monitored throughout the pre-injury and post-injury time period and while the athlete demonstrated a high degree of consistency during the data collection time period, the reported workloads approximated the total workload incurred by the athlete.

Neuromuscular Testing

Dual Force Plate Vertical Jump Force-Time Assessments

Countermovement (CMJ) and squat jump (SJ) force-time assessments on a dual force plate system were conducted regularly throughout the off-snow training periods in the pre-injury and post-injury periods. The standard protocols included: (1) 5-jump CMJ test using a self-determined depth; (2) 5-jump SJ test using a standardized depth of 90° of knee flexion; (3) 80 s repeated squat jump test using a standardized depth of 90° of knee flexion (total jumps per test: $n = 20$); (4) loaded CMJ test using three loading conditions including no external load, and an external load equal to ≈30% and ≈60% of body mass (Total CMJ tests conducted: $n = 37$; Total SJ tests conducted: $n = 36$; Total 80 s repeated SJ tests conducted: $n = 6$; Total loaded jump tests conducted: $n = 6$). All jump tests were performed with the hands placed firmly on the hips except for the loaded CMJ test in which the athlete held a trap bar (hex bar) whereby the external load was positioned at the level of the hip joint.

A detailed explanation of the vertical jump testing protocol and force-time analysis procedures have been described elsewhere (Jordan et al., 2015b, 2017b, 2018). Briefly, the vertical ground reaction force (Fz) from the right and left legs were measured simultaneously using a dual force plate system (Accupower Force Platform, AMTI, Watertown, Massachusetts, USA) at a sampling frequency of 1,500 Hz and recorded on a personal computer (MyoResearch Version 3.8, Noraxon, Scottsdale, Arizona, USA). Data were exported and analyzed using a custom-built computer program (Matlab R 2018b, Mathworks, Natwick, Massachusetts, USA). The velocity of the body center of mass (BCM) was obtained by time integration of the instantaneous acceleration signal (Fz/body mass – g) calculated from the total Fz, summed from the right and left limbs. Mechanical muscle power exerted on BCM was derived continuously throughout the jumping movement by calculating the instantaneous product of Fz and BCM velocity. Jump height was determined from the BCM vertical velocity at the instant of ground toe-off [Jump Height = Takeoff Velocity^2/2g] (Linthorne, 2001).

Vertical Jump Force-Time Asymmetry Assessment

An interlimb vertical jump force-time asymmetry index (AI) was calculated for discrete jump phases in the SJ and CMJ. For the CMJ, the total impulse was calculated by time integration of Fz over the eccentric deceleration phase and concentric phase, respectively (Jordan et al., 2015b). For the SJ, the early takeoff phase (initiation of the SJ to the peak of Fz in the concentric phase) and the late takeoff phase (peak Fz to the point of toe-off) were determined. The right and left total impulse were compared using a 5-jump mean AI using the following formula:

$$AI = \left(\frac{Right\ Impulse - Left\ Impulse}{Maximum\ of\ Left\ and\ Right\ Impulse}\right) * 100$$

80 s Repeated Squat Jump Test

A detailed description of the 80 s repeated SJ test can be found elsewhere (Jordan et al., 2017b). Briefly, the participant descended to the squat jump start position with the hands placed firmly on the hips and held this position for 4 s. A metronome timer indicated the start of the test that was set to repeat every 4 s. Following each maximal jump, the participant landed back in the squat jump start position and maintained this position until they were cued for the next jump by a strong verbal command from the tester. The participant performed 20 maximal jumps over the 80 s jump-test protocol. The SJ mean power, takeoff velocity and AI were averaged over sets of five jumps (Set 1 = Jumps 1–5; Set 2 = Jumps 6–10; Set 3 = Jumps 11–15; Set 4 = Jumps 16–20) allowing performance fatigability to be assessed by comparing the outcome measures in Set 4 with the outcome measures obtained in Set 1.

Loaded Countermovement Jump Test

A three-point takeoff velocity vs. external load profile was determined by having the participant perform 5 CMJs with and without an external load corresponding to ≈30 and 60% of body mass (García-Ramos et al., 2018). The takeoff velocity was obtained from the velocity-time curve of the BCM at the instant of ground toe-off. The net eccentric deceleration impulse was also calculated by time integration of Fz between the point of the minimum downward velocity to the zero-velocity time point corresponding to the lowest position of the BCM prior to the initiation of the ascent phase. Subsequently, the line of best fit was determined between the three data points to obtain the slope, the extrapolated maximum velocity intercept (V_0) and the extrapolated maximum external load intercept (F_0). The eccentric deceleration impulse vs. load profile was assessed using a polynomial line of best fit.

Rate of Force Development and Maximal Strength Assessments

Maximal voluntary contractions (MVCs) of isometric leg press, knee extension and knee flexion were conducted in the post-surgery time period (isometric leg press tests: $n = 3$; post-surgery time intervals: 4, 6, 17 months; isometric knee extension/flexion tests: $n = 4$; post-surgery time intervals: 6, 8, 11, and 17 months). The participant was instructed to perform all isometric testing "as fast and as hard as possible." Isometric leg press tests were performed on a custom-built seated leg press dynamometer instrumented with a single-axis force plate (PASCO, PS-2141, California, USA) and force was sampled at 1,000 Hz. The participant was seated in the leg press rig and instructed to hold a steady baseline force (100 N) with feedback provided by a visual display. Based on the verbal cues of the tester, the participant then performed 3 × 3 s MVCs of isometric leg press separated by a 20 s rest period.

The isometric knee extension and flexion testing was performed on a Cybex dynamometer instrumented with a third-party load cell (Omega, LC703-500, Stamford, Connecticut, USA) and force was sampled at 1,500 Hz (MyoResearch Version 3.8, Noraxon, Scottsdale, Arizona, USA). For the knee extension trials, the participant was positioned in a seated position with the knee joint angle set at 70° of knee flexion. The tester then instructed the participant to perform 3 × 3 s MVCs of isometric knee extension separated by a 20 s rest period. The isometric knee flexion testing was performed in the same manner except

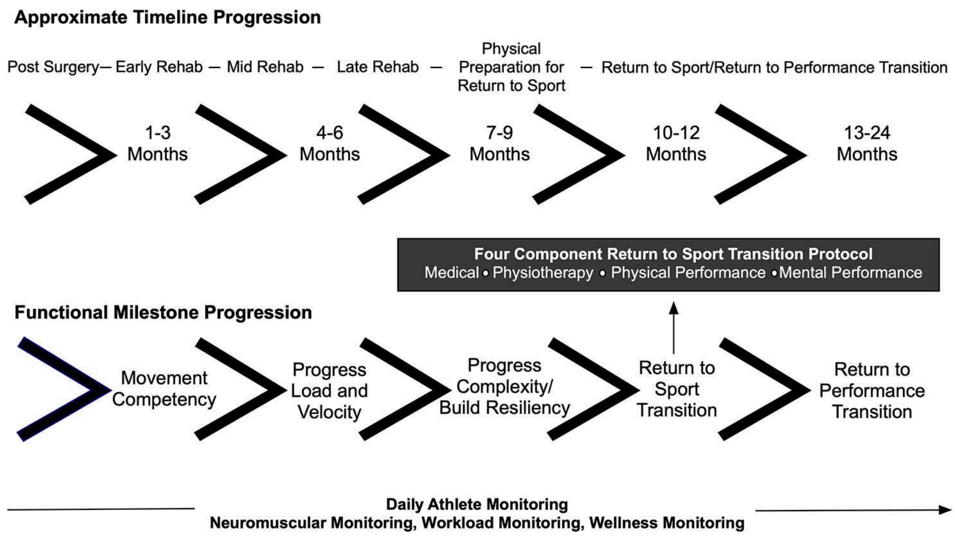

FIGURE 1 | Milestone and timeline progression used in the return to sport training plan.

the athlete was positioned in a prone position (hip flexion angle = 0°). Visual feedback and strong verbal encouragement were provided throughout the testing protocol.

The moment arm (distance from the axis of rotation to the point of force application) of the shank was obtained to calculate knee extensor and knee flexor torque. The isometric force-time (leg press) and torque-time (knee extension and flexion torque) curves were smoothed (Matlab "smooth" function using 33 ms centered moving average window). A 200 ms average around the peak value was calculated to obtain the maximum torque and maximum force. The derivative of the signal was then calculated to identify the peak RFD and rate of torque development (RTD). A 100 ms average around this timepoint was calculated to obtain the RFD and RTD.

OBSERVATIONS AND OUTCOMES OF THE RETURN TO SPORT TRANSITION

Interdisciplinary Performance Team Function

Building the Return to Sport Training Plan

Paralleling the periodization planning process for a macrocycle training plan used in elite sport, a return to sport training plan was developed the week following surgery by the IPT to address logistic factors (e.g., travel requirements, budget, resources, IPT meeting schedule, testing schedule), estimate the stages of tissue healing based on guidance by the orthopedic surgeon, establish the progression of functional neuromuscular milestones and provide an initial forecast for the recovery process. The ACL recovery forecast was based off an emerging dataset tracking the functional recovery of alpine skiers undergoing ACLR surgery alongside tracking of additional covariates such as the potential for associated injuries that may delay return to sport (e.g., chondral injury, meniscal tears, multi-ligament injuries) (Jordan et al., 2015a, 2017c).

The return to sport training plan was segmented into the post-surgical, early rehabilitation, mid rehabilitation, late rehabilitation, physical preparation for return to sport, return to sport transition, and return to performance phases (**Figure 1**). Consideration was given to both the post-surgical time period reflecting the importance of tissue healing and the milestone progression for movement competencies such as lower limb energy absorption ability, a critical performance factor in alpine ski racing. The return to sport training plan also aimed to ensure the IPT-athlete-coach triad had a communication framework and accountability structure for return to sport clearance. Notably, meeting times and dates for testing were scheduled in advance prior to the commencement of the return to sport training plan.

The return to sport protocol involved four components including input from the physician, physiotherapist, physical performance staff (strength and conditioning—S&C, sport science) and mental performance coach. The return to sport protocol was communicated to all athletes and coaches at the start of each season, including the injured athlete prior to the injury event, and this was deemed an important success factor for the team approach to building and executing the return to sport training plan. To this end, the leadership structure of the IPT was characterized as a *holacracy* or a self-managed team where the domain-specific experts emerged to lead in various phases of the return to sport transition.

Twelve 4-week training mesocycles were outlined in the return to sport training plan that progressed the athlete through to the end of the return to sport transition period (≈12 months post-surgery). Each mesocycle was further subdivided into: (1) a 3-day assessment period that included a medical evaluation, neuromuscular testing, anthropometric testing, fitness testing, and a meeting with the mental performance coach; (2) an IPT

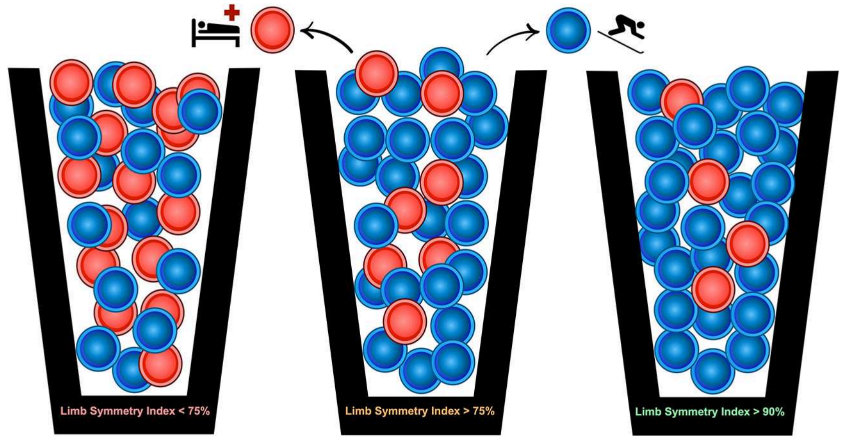

FIGURE 2 | A probability-based risk profile using three different quadriceps limb symmetry index thresholds is presented to contextualize the uncertainty surrounding the return to sport transition after ACL reconstruction surgery. Thresholds were chosen to reflect known associations between the quadriceps limb symmetry index and risk of ACL reinjury (Grindem et al., 2016).

debrief and program planning meeting where the findings of the assessments were integrated into a targeted training program; (3) an IPT-athlete-coach debrief meeting; (4) training program orientation sessions with the athlete that were attended by the physiotherapist, S&C coach and sport scientist enabling the training and rehabilitation plans to be adjusted if required; (5) execution of the 3-week training cycle; and finally (6) a recovery microcycle (3–5 days in duration). An athlete monitoring system that included neuromuscular monitoring, off-snow/on-snow workload monitoring and an evaluation of the athlete's recovery status (data not presented) underpinned the return to sport training plan.

The Interdisciplinary Performance Team's Role in Managing Uncertainty

A key function of the IPT was to manage uncertainty surrounding the return to sport transition alongside monitoring the athlete's advancement so that progressions/regressions could be made as required. Despite the best efforts of the IPT to clearly communicate the return to sport protocol, it was impossible to accurately predict the athlete's actual progression through the return to sport training plan. Return to sport after ACLR is a complex process with few certainties and implications for both erroneously accelerating or delaying an athlete's timeline for return to sport exist. To this end, objectively determined milestones and neuromuscular monitoring supported the return to sport process and permitted the IPT to manage the inherent uncertainty, high expectations, and potential barriers to a successful return to sport.

The uncertainty around return to sport decision making was communicated using a simple probability example showing an image of three buckets containing blue chips and red chips (**Figure 2**). The uncertainty of the return to sport transition after ACLR can be characterized by the presence of red chips and blue chips in all three buckets, differing only in terms of their relative proportions. In this example, drawing a red chip represents a reinjury while drawing a blue chip represents a successful return to sport. While red chips exist in all three buckets, the chances of drawing a red chip are smallest in the third bucket. This analogy was used to improve discussions between the athlete and IPT especially around factors such as whether or not to pursue an early return to sport.

Workload Monitoring

Sessional internal workload (sRPE—AU) measurements are shown in **Figure 3**. While the athlete demonstrated a high degree of consistency throughout the 2012–2019 training and competition periods there were phases of the annual training cycle when workload monitoring was not performed (e.g., post-Olympic time period, post-season recovery time period, post-injury time period). In certain instances, technological limitations precluded logging (e.g., during training periods in the Southern hemisphere where internet access was limited). For example, a cessation in logging occurred between August-November of 2016 due to this factor. Nevertheless, logging throughout the post-injury period enabled the IPT to track the workload progression to ensure adequate recovery was prescribed and that the accumulated workload was sufficient to support the demands of on-snow training in the return to sport phase. The relationship between restoring sport-specific workload capacity and the risk of ACL reinjury is unclear, but it seems important to ensure that an ACLR athlete has sufficient physical reserves to support return to sport training.

Sharp decreases in workload occurred after the 2014 Olympic Winter Games due to an upper body injury sustained at the Olympics. Workloads also decreased substantially after the ACL injury sustained in late November 2017. Normal logging resumed in January 2018 and the athlete demonstrated a steady increase in workload between January 2018 and June 2018 prior to the first return to snow camp in early July 2018. Workload decreased through the return to snow/return to performance transition (October-November 2018) with the first race occurring in late

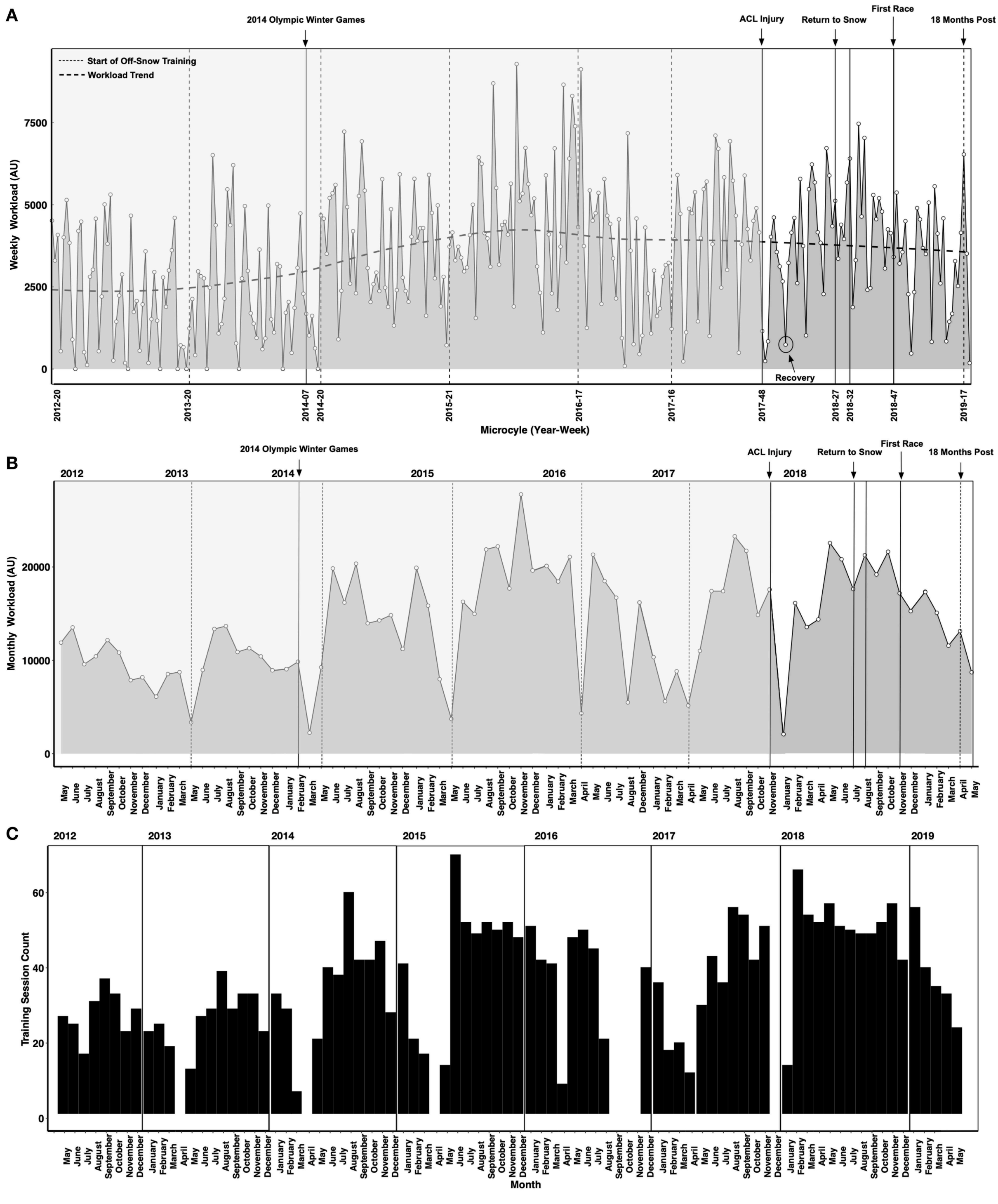

FIGURE 3 | Weekly **(A)** and monthly **(B)** internal workloads (sessional rating of perceived exertion method—sRPE) in arbitrary units (AU). Vertical lines represent time points of interest. An instance of a planned recovery microcycle is highlighted (circle). **(C)** Depicts the count of logged training sessions, including periods when no logging occurred. Periods when no logging occurred are not shown in **(A,B)**.

November 2018. The workload composition (i.e., the workloads of different program elements such as strength training) is not shown in **Figure 3A**. This is a key consideration as a substantial workload was incurred due to the demands of rehabilitation. Periodic decreases in workload (i.e., recovery microcycles) can be observed throughout the rehabilitation and physical preparation phases prior to the first return to snow camp shown in **Figure 3A**. Rehabilitation after serious injuries like ACL tears requires a considerable amount of physical and mental energy from the athlete. In elite sport, periods of high stress are often followed by planned recovery in which the workload (intensity, volume and density) are decreased to promote positive physical adaptation and avoid maladaptation. Thus, an integral component of the return to sport performance plan shown here includes planning and periodization methodologies aimed at accounting for the stress of rehabilitation, the requirement to restore physical work capacity to pre-injury levels and avoid preventable setbacks.

Neuromuscular Testing and Monitoring

Milestones and Progressions

There is no scientific consensus on a sport-specific return to sport protocol for alpine ski racers post-ACLR surgery. As such, the return to sport training plan and protocol presented in this case study were arrived at by the IPT based on the collective domain-specific expertise of the group, general recommendations in the scientific literature on return to sport protocols for ACL injured athletes, and an emerging body of knowledge generated by the IPT based on several years of consistent and routine monitoring of ACLR athletes. The objectives of the neuromuscular testing and monitoring approach were 5-fold: (1) use objectively determined, standardized and repeatable off-snow tests that reflect the demands of alpine ski racing; (2) employ a serial *athlete monitoring* approach vs. a single-time-point *clearance* approach; (3) use the results of the neuromuscular tests to drive the training and rehabilitation program design process; (4) spur better conversations amongst the IPT in an effort to manage the complexity and uncertainty of the return to sport process after ACLR; and (5) to assess and restore the basic functional properties of the neuromuscular system (e.g., maximal strength, RFD, the force-velocity relationship, the strength curve) alongside redeveloping movement competencies that were typically evaluated subjectively by the IPT members.

Figure 4 depicts a framework for guiding the return to sport transition including consideration for tissue healing, movement competencies, functional milestones, and work capacity. The initial focus post-surgery included optimizing tissue healing, restoring range of motion, normalizing gait patterns, and increasing thigh muscle volume. Thigh muscle volume was assessed consistently throughout the return to sport training plan through anthropometric testing. This data is not presented. The athlete was sequentially cleared throughout the return to sport training plan, and progressively more challenging movement competencies were introduced, such as progressing from squatting and jumping in the sagittal plane to jumping in the frontal plane and then to high velocity change of direction movements.

The milestones achieved in the previous phase directed the IPTs strategy on an on-going basis. For example, maximal muscle strength (i.e., maximum muscle force) was trained and monitored at the end of each 4 week training period in the early and mid-phases of rehabilitation. Once maximal isometric strength asymmetries presented below 10%, higher velocity movement competencies in the sagittal and frontal plane were introduced. This highlights a significant difference between a time-based and milestone-based approach. Interlimb vertical jump asymmetry assessments were routinely performed on a dual force plate system and used to monitor functional recovery of the athlete. Importantly, numerous pre-injury neuromuscular testing sessions, including vertical jump asymmetry assessments, provided a baseline for comparison, which is important given that the non-surgical limb may also detrain consequent to an ACL injury. This further highlights the significance of, and rationale for, regularly conducting neuromuscular testing in athletes at risk for ACL injury.

Neuromuscular testing also included consideration for the effects of common comorbidities on muscle strength and power. For example, a semitendinosus tendon autograft is the most common ACLR surgical procedure employed with Canadian alpine skiers (Jordan et al., 2017c). And, this procedure is known to cause long-term hamstring strength deficits, especially at larger angles of knee flexion (>70° knee flexion) (Konrath et al., 2016). Thus, the strength curve of the hamstrings and quadriceps, and RFD ability, that is unique from the capacity to generate high muscle force, were routinely assessed throughout the return to sport and the return to performance phases (Jordan et al., 2015c). Prior to the return to sport transition, the athlete's workload capacity, aerobic power, and power endurance were assessed. Importantly, the IPT evaluated the stability of movement competencies and functional asymmetries when the athlete was under pressure (e.g., increased cognitive task demands) and fatigued. Finally, neuromuscular monitoring was conducted throughout the return to sport and return to performance phases, given the prevalence of ACL reinjury in the first 24 months post ACLR surgery.

Vertical Jump Force-Time Asymmetry Testing

Vertical jump force-time asymmetry testing on a dual force plate system was undertaken as a component of the routine athlete monitoring program both before and after injury (**Figure 5**). This assessment has been used previously with alpine ski racers (Jordan et al., 2015b, 2018), elite soccer players with lower body injury (Hart et al., 2019), and to evaluate neuromuscular function in ACLR athletes (Baumgart et al., 2017; Miles et al., 2019). The vertical jump force-time asymmetry assessment is a standardized and repeatable test that is easily employed in the daily training environment of elite athletes. It also permits an evaluation of eccentric vs. concentric movement abilities, and as eccentric movements occur frequently in alpine ski racing, the IPT could evaluate eccentric movement abilities throughout the return to sport training period in a standardized manner.

Figure 5 depicts the pre-injury and post-injury vertical jump force-time asymmetries. An elevated interlimb asymmetry index beyond this threshold was noted at the first testing point for the concentric phase of the CMJ and the late takeoff phase of the SJ (Asymmetry Index >25%). There was a steady recovery observed in the CMJ eccentric deceleration phase asymmetry index to baseline values at the return to sport transition. However, CMJ concentric phase and SJ late takeoff phase asymmetries remained elevated compared to baseline measurements until 18 months

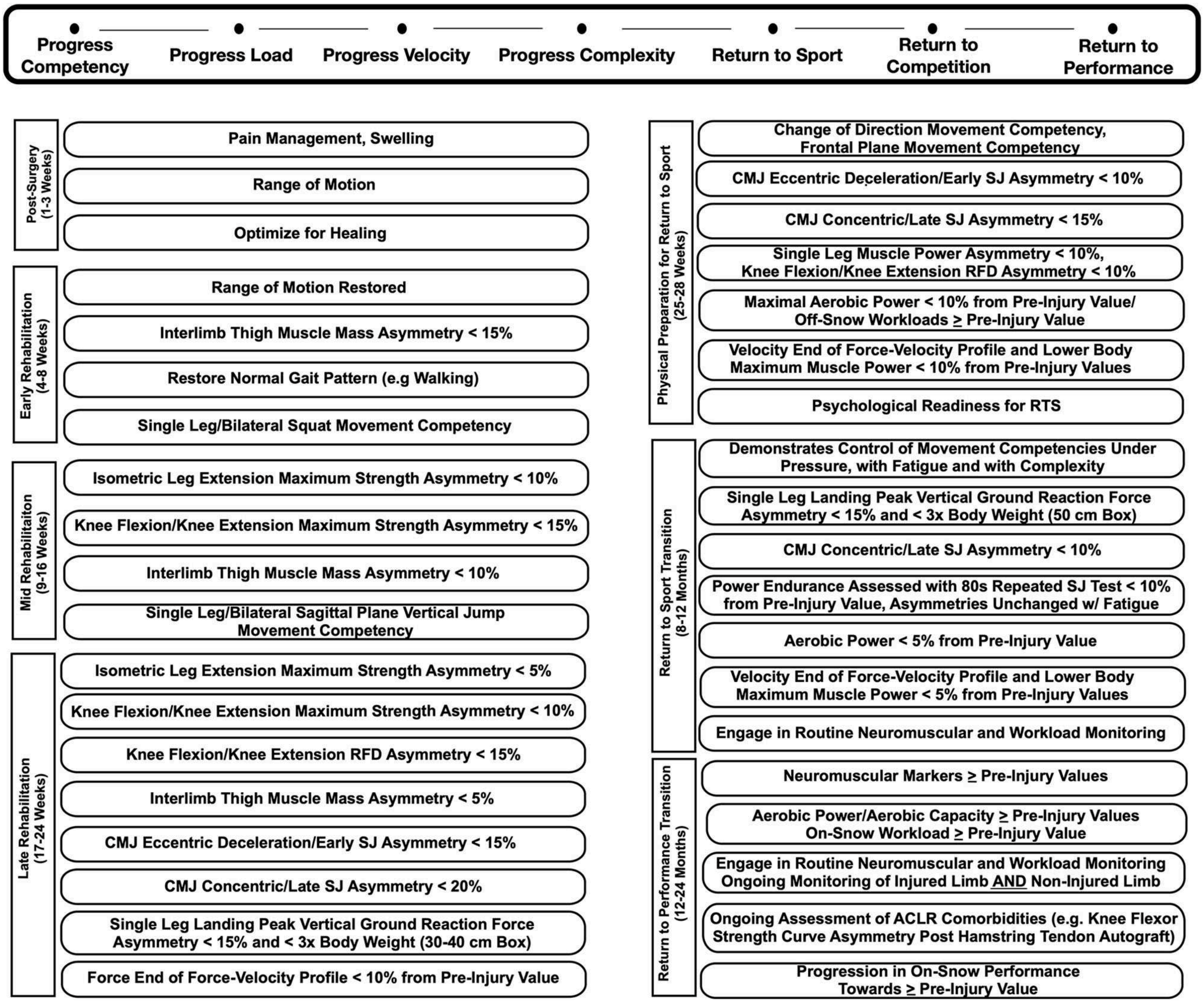

FIGURE 4 | Target neuromuscular milestone and workload progressions post ACL reconstruction surgery. CMJ, Countermovement Jump; SJ, Squat Jump; RFD, Rate of Force Development; RTS, Return to Sport; Eccentrric Decel, Eccentric Deceleration.

post-surgery. An unanticipated loading strategy was seen in the final SJ asymmetry test of the return to sport transition. Notably, increased asymmetry reflecting ACLR limb dominance was found in the early takeoff phase of the SJ, whereas increased asymmetry reflecting contralateral limb dominance was observed in the late takeoff phase of the SJ. A shift in the interlimb asymmetry throughout the range of motion of the vertical jump has been previously observed in ACLR alpine skiers (Jordan et al., 2015b). The reason for this is unknown, but it suggests that the force-time curve should be characterized in its entirety when evaluating vertical jump asymmetries. Further, contrary to evaluating limb symmetry in strength or RFD, the vertical jump can be considered a complex movement where no two jumps are the same and no jump is perfectly symmetrical. Thus, asymmetries may be best understood by characterizing the mean and variation over multiple movement cycles.

Vertical jump force-time asymmetries were also affected by fatigue in the 80 s repeated SJ test (**Figure 6**). This test was developed to evaluate an alpine ski racer's power-endurance and lower body RFD abilities over a time period that is similar to a typical training run or ski race (Jordan et al., 2017b). Not only can power-endurance and work capacity be assessed with this test but also the acute effects of fatigue on interlimb asymmetries.

A key observation shown in **Figure 6** is that the interlimb asymmetry index in the *late takeoff phase* of the SJ declined with fatigue from > 10% in Set 1 (first 5 jumps at the start of the test) to <10% in Set 4 (last 5 jumps at the end of the test) for the two post-injury measurements, a pattern not observed in the pre-injury or 18 months post injury tests. This reflected the athlete becoming *more* symmetrical with fatigue due to a decrease in force generated by the non-surgical contralateral limb, presumably due to the acute effects of fatigue. There

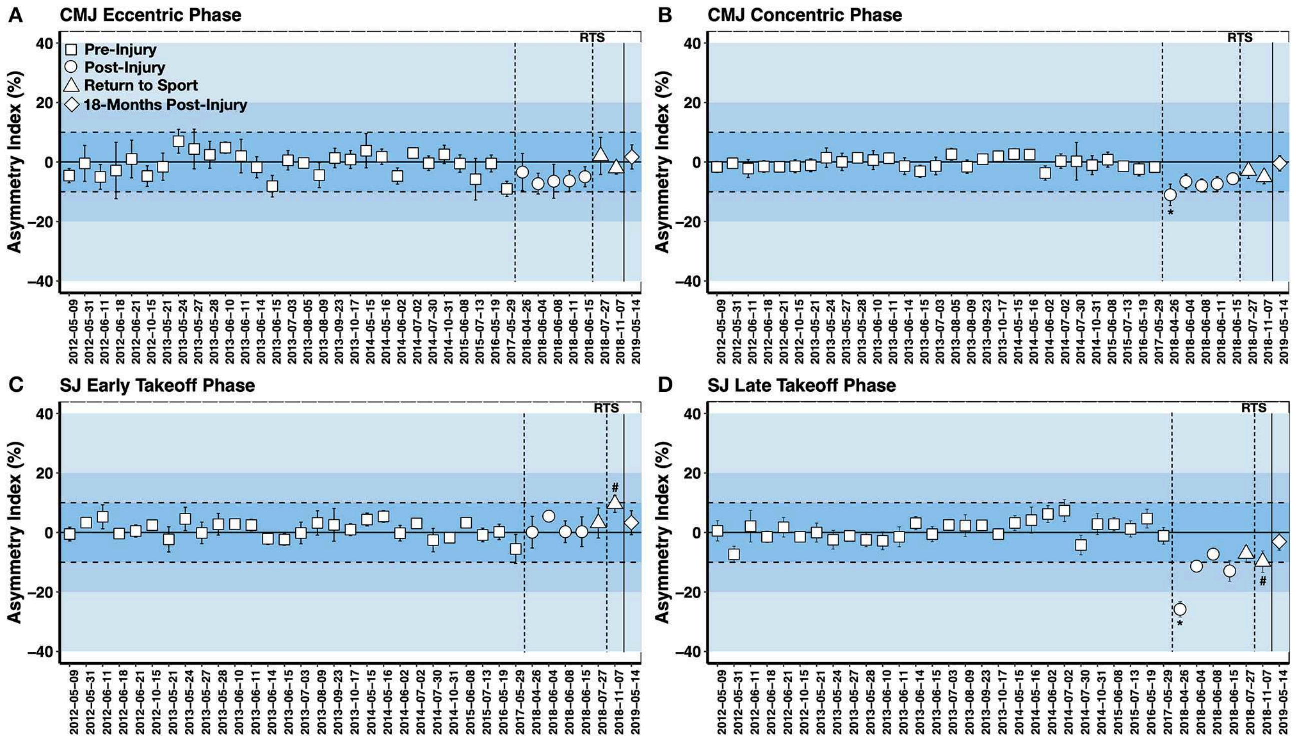

FIGURE 5 | Squat jump (SJ) and countermovement jump (CMJ) force-time asymmetry assessments pre-injury, post-injury, at return to sport (RTS) and 18 months post-surgery (**A**: CMJ Eccentric Deceleration Phase; **B**: CMJ Concentric Phase; **C**: SJ Early Takeoff Phase; **D**: SJ Late Takeoff Phase). Data are shown as the five-jump mean asymmetry index ± SD (positive value = ACLR limb dominance; negative value = contralateral limb dominance). SJs demonstrating a small amplitude countermovement were discarded from the analysis. *First asymmetry test post-injury; # observation of shift in the interlimb asymmetry at teh return to sport phase.

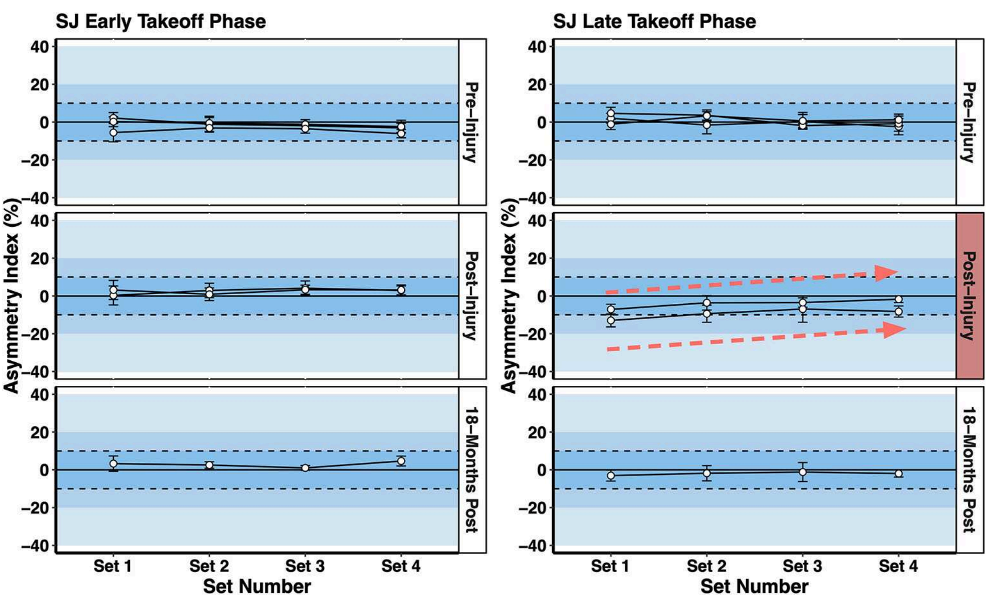

FIGURE 6 | Squat jump (SJ) asymmetries in the early takeoff phase (initiation of jump to the peak vertical ground reaction force) and late takeoff phase (peak vertical ground reaction force to toe-off) over the 80 s repeated SJ test. A comparison is made between pre-injury tests and post-injury tests. A decline in late takeoff phase asymmetry (i.e. increased symmetry) with fatigue (i.e., Set 1 vs. Set 4) was observed post-injury reflecting a decline in force generated by the contralateral limb.

is no concrete scientific evidence to support a link between neuromuscular fatigue and risk for ACL injury. However, elite alpine ski racers and expert stakeholders rank fatigue as a contributing factor to injury (Spörri et al., 2012). Further, there is a higher prevalence of secondary ACL injury sustained by the contralateral limb in ACLR alpine ski racers compared to the ipsilateral limb (Pujol et al., 2007; Jordan et al., 2017c). There is no evidence to support a causal relationship between the observations presented in this case study and the potential for ACL reinjury. However, assessing work capacity, power-endurance, and ability to maintain movement competencies while fatigued, were important components of the return to sport training plan presented here.

Lower Body Mechanical Muscle Function, Maximal Muscle Strength, and Muscle Power

Lower body mechanical muscle function was assessed throughout the return to sport training plan including assessments of: (1) lower body maximal muscle power and power-endurance assessed in the CMJ and SJ; (2) lower body eccentric abilities including lower limb stiffness that measures the ability to reverse the downward acceleration of the BCM assessed in the CMJ; (3) knee extensor, knee flexor and leg press maximal strength and RFD ability evaluated during isometric MVCs; (4) CMJ takeoff velocity vs. load and eccentric deceleration impulse vs. load relationships; and (5) an evaluation of the knee flexor strength curve (i.e., torque-joint angle relationship) given the athlete underwent a semitendinosus tendon autograft, a procedure that is known to impact knee flexor torque at specific joint angles.

The aim of the testing battery was to assess a range of strength and movement abilities that are important for alpine ski racing performance using standardized and repeatable tests, including eccentric force-time abilities that have been shown to distinguish elite alpine ski racers from development-level skiers (Jordan et al., 2018). Further, the testing battery was also used to assess different muscle properties (force-velocity relationship, torque-joint angle relationship) with an aim to pinpoint deficits so that the rehabilitation and retraining could be tailored to the athlete's specific needs. **Figure 7** depicts a selection of measures obtained from the CMJ and SJ analysis, including the loaded CMJ testing shown in the bottom two panels (**Figures 7E,F**). However, pre-injury measures are not shown for the loaded CMJ testing.

CMJ mean power and lower body limb stiffness were not restored to pre-injury levels at the 18 months post-injury timepoint. While the interlimb asymmetry in limb stiffness was negligible at the 18 months post-injury time point, it can be seen that the total limb stiffness had still not fully recovered to the pre-injury mean value. Only total power in the 80 s repeated SJ test (the sum of the mean power from all 20 jumps) and the CMJ net eccentric deceleration impulse were back to or above the pre-injury mean value at 18 months post-injury. However, the CMJ net eccentric deceleration impulse, representing the athlete's ability to reverse the downward acceleration of her BCM, may not reflect the demands of alpine ski racing given that elite alpine ski racers are exposed to near maximal eccentric loading exceeding body mass (Berg et al., 1995). Thus, the loaded CMJ protocol assessed the skier's ability to manage external loads greater than her body mass. At the 18 months post-injury testing timepoint (**Figure 7F**), while the unloaded CMJ eccentric deceleration impulse remained above the pre-injury mean value and the return to sport testing timepoint at 9 months post-injury, decreased force generating capacity for the high load condition was observed. This likely reflected a loss of maximal muscle strength, a finding that could be used to optimize the off-snow training period and the return to performance transition.

Finally, MVCs of isometric leg press, isometric knee extension and isometric knee flexion were conducted throughout the return to sport training phase (**Figure 8**). Pre-injury values are not displayed as the tests were added after the injury was sustained. In addition to measuring the maximal leg press force and maximal knee extensor/flexor torque, an average slope analysis was conducted to assess the athlete's rapid force generating RFD ability. The physiological determinants of maximal muscle strength include muscle architecture (e.g., physiological cross sectional area—PCSA) and motor unit recruitment ability (Maffiuletti et al., 2016). While the physiological determinants of the late phase RFD (>100 ms from the onset of contraction) include factors influencing maximal muscle strength, neural factors such as the motor unit firing rate (rate coding) and doublet firing alongside the intrinsic muscle fiber properties are the primary determinants of early RFD (<100 ms from the onset of contraction) (Maffiuletti et al., 2016).

The recovery of leg press force, knee extensor torque and knee flexor torque are shown in **Figure 8**. Interestingly, the non-injured limb maximum knee extensor torque and RTD declined over the post-injury period, leading to a reduction in the interlimb asymmetry index. In fact, at the 18 months post-injury timepoint, the ACLR limb produced higher knee extensor torque compared to the non-injured limb (Asymmetry Index = 9%, reflecting ACLR limb dominance). Again, monitoring the neuromuscular function of both the ACLR limb and non-injured limb is critical. This observation further emphasizes the importance of evaluating the limb-specific torques, alongside the interlimb asymmetry index throughout the return to sport/return to performance transition, to ensure both limbs are sufficiently strong. Consistent with the scientific literature, a slower recovery in the knee extensor/knee flexor RFD ability was also noted throughout the post-injury period and return to sport transition. However, the leg press maximum force and RFD asymmetry indexes had recovered to below 3% by the 18 months post-injury testing session (**Figures 8C,D**).

DISCUSSION

The main objective of this paper was to present a return to sport training plan and return to sport clearance protocol, underpinned by neuromuscular testing and workload monitoring, for a female elite alpine ski racer who sustained an ACL injury. This paper also presented the functional role of the IPT, including practitioners in mental performance, sports medicine, orthopedic surgery, physiotherapy and physical performance sciences (S&C, sport science) in supporting the

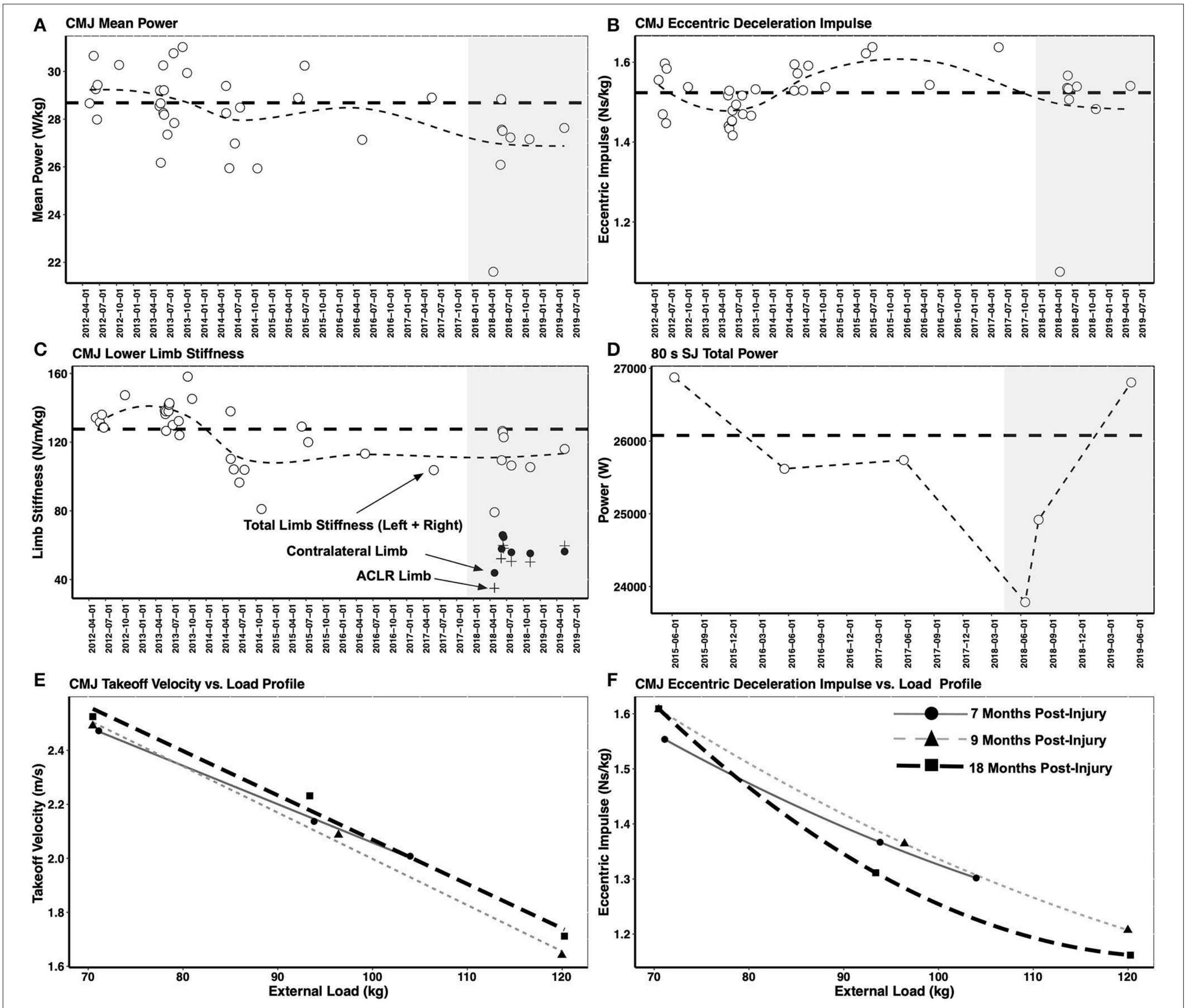

FIGURE 7 | (A–D) Depict lower body mechanical muscle function assessed in the countermovement jump (CMJ) and squat jump (SJ). Shaded gray zone depicts the post-injury period. Thick horizontal dashed line shows the mean pre-injury value. Thin dashed line depicts trendline over the testing period. To highlight the importance of considering the strength of each limb independently alongside a measure of interlimb asymmetry, the ACLR limb stiffness (+ symbol) and non-injured limb stiffness (• symbol) are shown alongside the total limb stiffness (o symbol). While the interlimb asymmetry in limb stiffness was negligible at the 18 months post-injury time point, it can be seen that the total limb stiffness had still not fully recovered to the pre-injury mean value. **(E)** Shows the CMJ takeoff velocity vs. load profile and **(F)** shows the CMJ eccentric deceleration impulse vs. load profile in the post-injury testing period.

return to sport and return to performance transition after ACL injury.

The return to sport/return to performance transition after ACL injury is a multifactorial process characterized by complexity and many uncertainties (Buckthorpe, 2019; Burgi et al., 2019). It is of critical importance after ACLR surgery to ensure tissues have had sufficient time to heal, a process that often requires more time than is allotted by return to sport timelines (Nagelli and Hewett, 2016). To this end, time from surgery was considered in the return to sport training plan presented here. However, there are few pragmatic and concrete measures of healing, and time from surgery has little bearing on functional capacities after ACL injury (Barber-Westin and Noyes, 2011; Grindem et al., 2016; Burgi et al., 2019; Cristiani et al., 2019). Thus, objective neuromuscular testing is recommended after ACL injury to evaluate functional milestones alongside a carefully planned and progressive return to sport training plan (Myer et al., 2006; Grindem et al., 2016; Buckthorpe, 2019). This seems especially important for alpine ski racers with ACL injury given the high risk for traumatic injury (Flørenes et al., 2009; Bere et al., 2014), the high lower body strength and work capacity demands involved in ski racing (Berg et al., 1995), the frequency

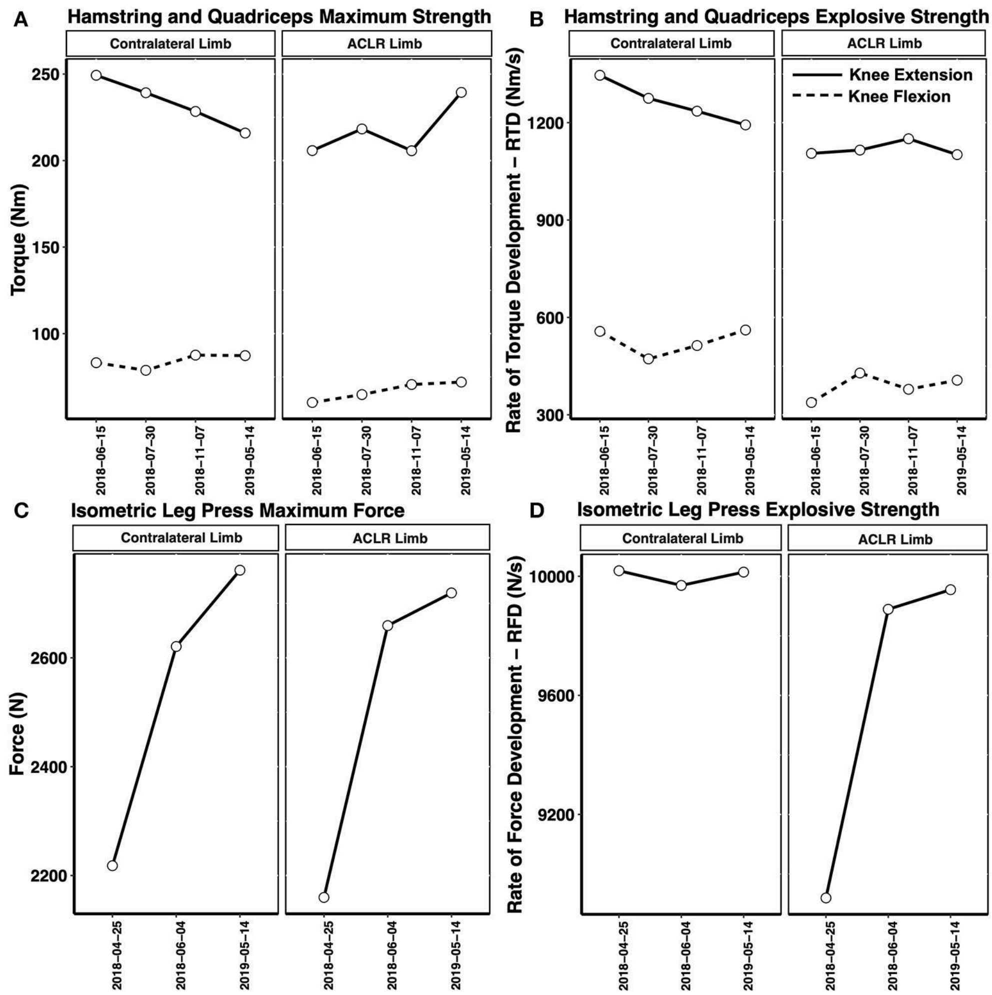

FIGURE 8 | Recovery of the isometric knee extensor/knee flexor maximum torque **(A)**, rate of torque development—RTD **(B)**, leg press maximum force **(C)**, and leg press rate of force development—RFD **(D)** in the post-injury period. A decrease in the non-injured limb knee extensor maximal torque and RTD was observed through to the 18 months timepoint. Hamstring and quadriceps RTD remained depressed compared to maximal torque at 18 months post-injury. A small interlimb asymmetry in leg press maximum force and RFD was noted at 18 months post-injury.

with which alpine skiers return to sport after ACL injury (Haida et al., 2016), and the prevalence of ACL reinjury (Pujol et al., 2007; Haida et al., 2016; Jordan et al., 2017c).

There are no evidence-based return to sport protocols or testing batteries for alpine ski racers with ACL injury, but developing this knowledge base is important (Jordan et al., 2017a). To this end, the return to sport testing protocol presented here included numerous tests that attempted to assess the movement competencies, strength abilities, and workload capacity of the athlete. While this protocol required specialized equipment and more time than traditional field testing, it was consistent with recommendations in the scientific literature of employing objectively determined tests that evaluate a range of neuromuscular abilities (Myer et al., 2006).

The neuromuscular testing battery included measures that have been shown to identify individuals at-risk for ACL reinjury, such as interlimb quadriceps strength symmetry (Grindem et al., 2016). Hamstring muscle strength was evaluated as well given the effects of the semitendinosus tendon autograft procedure on knee flexor torque (Konrath et al., 2016). Additionally, interlimb vertical jump asymmetries, permitting an evaluation of eccentric/concentric movement abilities, were evaluated using a dual force plate system. This approach has recently become more common for evaluating neuromuscular function in ACL injured athletes (Jordan et al., 2015b, 2018; Baumgart et al., 2017; Hart et al., 2019; Miles et al., 2019). The present protocol also conducted an assessment of power-endurance including the acute effects of fatigue on interlimb asymmetries. While there is no link between fatigue and the risk for ACL injury/reinjury, fatigue may affect the lower body force-generating capabilities of ACL injured athletes compared to non-injured controls (Jordan et al., 2017b). Consistent with this idea, the ACL injured athlete highlighted in this case study showed a reduction in SJ interlimb asymmetry with fatigue, reflecting less force generated by the non-injured limb in the final 20 s of the 80 s repeated squat jump test. This pattern was not observed at the 18 months post-injury timepoint and the total mechanical power produced in the 80 s SJ test had been restored above the pre-injury values by the final test.

In the present case study, the neuromuscular test battery appeared sensitive to the recovery process after ACL injury. Notably, the interlimb asymmetry index for the late takeoff phase of the SJ and concentric phase of the CMJ tracked most consistently with the time-course recovery following ACL injury (*c.f.* **Figure 5**). In support of this notion, the interlimb asymmetry indexes in these jump phases were previously shown to distinguish elite alpine ski racers with ACLR from skiers without ACLR (Jordan et al., 2015b). However, more importantly, the test battery allowed the IPT to pinpoint trainable deficits that could be addressed throughout the return to sport training plan. Additionally, an *athlete monitoring* strategy was employed vs. a single discrete time point *clearance* approach. The recovery after ACLR surgery is lengthy, often taking many years (Jordan et al., 2015a) and the prevalence of ACL reinjury is greatest in the first 2 years after ACLR surgery (Paterno et al., 2012, 2014). Thus, the return to sport transition, often occurring between 9 and 12 months after ACLR surgery, fails to account for the period with the highest risk of reinjury and the fact that ACLR athletes often wish to restore their pre-injury performance level (i.e., return to performance), a process that may require several years. The framework presented here attempted to account for the dynamic transitional nature of the recovery process after ACLR surgery, including consideration for the rehabilitation, return to sport and return to performance phases.

Despite the recommendation that objective testing be conducted in athletes with ACL injury to safeguard against reinjury, there appears to be limited evidence to support this notion (Burgi et al., 2019; Webster and Hewett, 2019). In fact, while passing commonly performed return to sport testing batteries was associated with a lower risk of ACL re-rupture, it was associated with a 3x higher risk for contralateral ACL injury (Burgi et al., 2019; Webster and Hewett, 2019). This highlights the importance of monitoring neuromuscular function in both the ACLR limb and non-injured limb alike throughout the return to sport/return to performance transition. In the present case study, the non-injured limb demonstrated a decline in quadriceps strength and RFD through to the 18-month post-injury time point.

Not only might RFD analysis provide additional insight into the recovery of an ACLR athlete, but it has also been shown that quadriceps and hamstring RFD remain persistently depressed in ACLR patients, recovering more slowly than maximum muscle strength. Active tissues, like skeletal muscle, including the quadriceps and hamstring muscles, are important for absorbing external energy to protect passive tissues like the ACL. Importantly, the hamstring muscle group acts as an ACL synergist counteracting anterior shear forces and tibial rotation that cause ACL strain (Barrata et al., 1988). Maximum muscle force is attained more than 500 ms after the onset of contraction, and as ACL injury events in alpine ski racing occur in much shorter time frames (i.e., $<$100 ms), hamstring RFD may be particularly important for providing dynamic knee joint stabilization to protect against ACL injury/reinjury (Jordan et al., 2015c). As functional testing like single leg hopping may be of little predictive value for identifying athletes at risk for ACL reinjury (Grindem et al., 2016), hamstring/quadriceps strength assessments, including assessing RFD ability, is important to evaluate in ACLR athletes throughout rehabilitation and the return to sport training phase. Despite observing a recovery in the interlimb vertical jump asymmetries, muscle strength and power deficits compared to the pre-injury mean value remained 18 months post-injury. This highlights the importance of baseline testing for athletes at-risk for ACL injury to provide benchmarks for comparison in the event of an injury. Based on the data presented here, a full recovery after ACL injury was not equated with a full return to sport and competition.

In addition to neuromuscular testing, return to sport protocols should also consider the psychological readiness of the athlete given its association with the risk for ACL reinjury (McPherson et al., 2019). Furthermore, the return to sport transition can be supported by a team approach that involves interdisciplinary expertise (Wang et al., 2019). Psychological readiness was not evaluated objectively in the present case study, which is a limitation especially given that alpine ski racing is an extreme sport with a high risk for traumatic injury (Flørenes et al., 2009; Bere et al., 2014), and that many factors related to skier psychology have been identified by expert stakeholders as contributors to injury risk (Spörri et al., 2012). Nevertheless, the IPT functioned as a *holacracy* or a flat leadership structure where the opinions of the domain-specific experts were considered equally, including those pertaining to the athlete's psychological readiness.

Finally, the present case study included an assessment of internal workload (sRPE) as a component of the return to sport training plan with an aim to ensure the athlete had sufficient work capacity and physical reserves to support the return to snow training camps. To the authors' best knowledge, there are currently no scientific investigations into the validity of the sRPE method for measuring the internal workload in alpine ski racers, and the relationship between work capacity and ACL injury/reinjury risk remains unknown.

LIMITATIONS

There are limitations to the case study presented here. First, the generalizability of the present data to the elite alpine skiing population at large and to development-level alpine skiers is unknown. Scientific inquiry is also required to validate the proposed frameworks for safeguarding athlete health and safety following ACL injury. The physical demands of alpine ski racing, including the high forces and high velocities that are attained in an unpredictable environment (i.e., unknown and variable course conditions) are difficult to simulate in a controlled laboratory setting. Consequently, the neuromuscular tests that are proposed may be insufficient for evaluating the physical capacities of alpine skiers with ACL injury. To this end, wearable technologies such as inertial measurement units that can be worn during skiing may provide additional information to the IPT, including the ability to assess the relationship between off-snow neuromuscular testing indices and on-snow neuromuscular strategies that may be involved in ACL reinjury (Färber et al., 2018; Bessone et al., 2019). Finally, it is recognized that psychological readiness is an important determinant of return to sport readiness after ACL injury (McPherson et al., 2019). Psychological readiness was not assessed objectively in the present case study and this should be considered an important component of the return to sport transition after ACL injury given the extreme nature of alpine ski racing.

SUMMARY AND RECOMMENDATIONS

Alpine ski racing is an extreme sport with a high risk for ACL injury and high proportion of skiers will return to sport post-ACLR surgery. Alpine skiers with ACL injury are at increased risk for ACL reinjury, and the physical and psychological readiness of alpine ski racers can be compromised after ACL injury. Return to sport after ACL injury is a complex and uncertain transitional period in an athlete's career and the interdisciplinary performance team (IPT) can support the recovery process through a team-approach to rehabilitation that is underpinned by athlete monitoring, neuromuscular testing, planning and science. However, more work remains to be done to establish a valid return to sport testing protocol and the training methods to support elite alpine ski racers with ACL injury. There are several potential recommendations and considerations that emerge from this case study alongside findings from the scientific literature that can assist practitioners in building a return to sport training plan for alpine skiers with ACL injury:

- Assemble team-oriented individuals including practitioners with expertise in sports medicine, physiotherapy, strength & conditioning, sport science/physiology, nutrition, biomechanics, and mental performance.
- Model the IPT off a *holacracy* whereby domain-specific-practitioners lead the discussion depending on the situation and the phase of the return to sport/return to performance transition. As return to sport after ACL injury is multifactorial, all members of the team, including the athlete, should feel empowered to communicate their concerns and opinions.
- Build a periodized return to sport training plan that follows accepted training principles, uses a functional milestone-based approach and details the phases through which the athlete will progress including the acute post-operative period, early/mid/late rehabilitation, return to sport transition and the return to performance transition. ACL reinjury typically occurs within the first 2 years post-injury so it is important that the return to sport training plan reflects this timeline.
- Alpine ski racers suffering ACL injury often sustain significant combined injury including multi-ligament injuries, meniscal tears and chondral injury. These factors delay typical return to sport timelines and should be factored into the return to sport training plan.
- The IPT should work closely with the coach to develop a progressive and appropriate return to snow plan that factors in the psychological readiness and physical readiness of the ACLR skier.
- Communicate the return to sport protocol in advance, prior to the occurrence of injuries, translating the concept of a milestone-based approach vs. time-based approach to coaches, athletes and members of the IPT.
- Start building an athlete-specific pre-injury profile, including baseline assessments of neuromuscular function, physical fitness, and workload capacity that can be used as benchmarks for comparison after ACL injury to guide the return to sport training plan.
- Workloads should be monitored and progressed throughout the return to sport transition so that an ACLR skier has sufficient physical reserves to endure the demands of return to snow training.
- A battery of standardized and reliable neuromuscular assessments that are objectively determined and specific to the demands of alpine ski racing should be employed to evaluate an alpine skier with ACL injury.
- Interlimb asymmetries are a useful indicator of recovery after ACL injury but it is important to ensure both limbs are sufficiently strong given that ACL injury impacts both the injured and non-injured limbs.
- Employ an *athlete monitoring* approach that tracks the athlete throughout the return to sport/return to performance transitions instead of a *discrete timepoint clearance* approach.

DATA AVAILABILITY STATEMENT

The datasets for this article are not publicly available because data pertains to Olympic athletes. Requests to access the datasets should be directed to MJ, mjordan@ucalgary.ca.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Calgary Research Ethics Board. The patients/participants provided their written informed consent to participate in this study. The animal study was reviewed and approved by University of Calgary Research Ethics Board.

AUTHOR CONTRIBUTIONS

MJ was responsible for preparing the manuscript. ML, NM, JB, MH and WH were responsible for data collection and data analysis. MH, SR and KM were responsible for medical milestones. All authors contributed to the concepts and framework presented in the manuscript.

REFERENCES

Ardern, C. L., Taylor, N. F., Feller, J. A., and Webster, K. E. (2014). Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. *Br. J. Sports Med.* 48, 1543–1552. doi: 10.1136/bjsports-2013-093398

Ardern, C. L., Webster, K. E., Taylor, N. F., and Feller, J. A. (2011). Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br. J. Sports Med.* 45, 596–606. doi: 10.1136/bjsm.2010.076364

Barber-Westin, S. D., and Noyes, F. R. (2011). Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. *Arthrosc. J. Arthrosc. Relat. Surg.* 27, 1697–1705. doi: 10.1016/j.arthro.2011.09.009

Barrata, R., Solomonow, M., Zhou, E., Letson, D., Chuinard, R., and D'Ambrosia, R. (1988). Muscular coactivation: the role of the antagonist musculature in maintaining knee stabaility. *Am. J. Sports Med.* 16, 113–122. doi: 10.1177/036354658801600205

Baumgart, C., Hoppe, M. W., and Freiwald, J. (2017). Phase-specific ground reaction force analyses of bilateral and unilateral jumps in patients with ACL reconstruction. *Orthop. J. Sport. Med.* 5, 1–9. doi: 10.1177/2325967117710912

Bere, T., Flørenes, T. W., Nordsletten, L., and Bahr, R. (2014). Sex differences in the risk of injury in World Cup alpine skiers: a 6-year cohort study. *Br. J. Sports Med.* 48, 36–40. doi: 10.1136/bjsports-2013-092206

Berg, H., Eiken, O., and Tesch, P. (1995). Involvement of eccentric muscle actions in giant slalom racing. *Med. Sci. Sport. Exerc.* 27, 1666–1670. doi: 10.1249/00005768-199512000-00013

Bessone, V., Petrat, J., and Schwirtz, A. (2019). Ground reaction forces and kinematics of ski Jump landing using wearable sensors. *Sensors* 19, 1–11. doi: 10.3390/s19092011

Buckthorpe, M. (2019). Optimising the late-stage rehabilitation and return-to-sport training and testing process after ACL reconstruction. *Sports Med.* 49, 1043–1058. doi: 10.1007/s40279-019-01102-z

Burgi, C. R., Peters, S., Ardern, C. L., Magill, J. R., Gomez, C. D., Sylvain, J., et al. (2019). Which criteria are used to clear patients to return to sport after primary ACL reconstruction? A scoping review. *Br. J. Sports Med.* 53:1154–1161. doi: 10.1136/bjsports-2018-099982

Cristiani, R., Mikkelsen, C., Forssblad, M., Engström, B., and Stålman, A. (2019). Only one patient out of five achieves symmetrical knee function 6 months after primary anterior cruciate ligament reconstruction. *Knee Surg. Sports Traumatol. Arthrosc.* 27, 3461–3470. doi: 10.1007/s00167-019-05396-4

Färber, S., Heinrich, D., Werner, I., and Federolf, P. (2018). Is it possible to voluntarily increase hamstring muscle activation during landing from a snow jump in alpine skiing? - A pilot study. *J. Sports Sci.* 37, 180–187. doi: 10.1080/02640414.2018.1488423

Flørenes, T. W., Bere, T., Nordsletten, L., Heir, S., and Bahr, R. (2009). Injuries among male and female World Cup alpine skiers. *Br. J. Sports Med.* 43, 973–978. doi: 10.1136/bjsm.2009.068759

Forsdyke, D., Gledhill, A., and Ardern, C. (2017). Psychological readiness to return to sport: three key elements to help the practitioner decide whether the athlete is REALLY ready? *Br. J. Sports Med.* 51, 555–556. doi: 10.1136/bjsports-2016-096770

Foster, C. (1998). Monitoring training in athletes with reference to overtaining syndrome. *Med. Sci. Sports Exerc.* 30, 1164–1168. doi: 10.1097/00005768-199807000-00023

García-Ramos, A., Pérez-Castilla, A., and Jaric, S. (2018). Optimisation of applied loads when using the two-point method for assessing the force-velocity relationship during vertical jumps. *Sports Biomech.* 12, 1–16. doi: 10.1080/14763141.2018.1545044

Grindem, H., Snyder-Mackler, L., Moksnes, H., Engebretsen, L., and Risberg, M. A. (2016). Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *Br. J. Sports Med.* 50, 804–808. doi: 10.1136/bjsports-2016-096031

Haaland, B., Steenstrup, S. E., Bere, T., Bahr, R., and Nordsletten, L. (2016). Injury rate and injury patterns in FIS World Cup Alpine skiing (2006-2015): have the new ski regulations made an impact? *Br. J. Sports Med.* 50, 32–36. doi: 10.1136/bjsports-2015-095467

Haida, A., Coulmy, N., Dor, F., Antero-Jacquemin, J., Marc, A., Ledanois, T., et al. (2016). Return to sport among french alpine skiers after an anterior cruciate ligament rupture: results from 1980 to 2013. *Am. J. Sports Med.* 44, 324–330. doi: 10.1177/0363546515612764

Hart, L., Cohen, D., Patterson, S., Springham, M., Reynolds, J., Read, P. (2019). Previous injury is associated with heightened countermovement jump force-time asymmetries in professional soccer players even after return to play. *Transl. Sport Med.* 2, 256–262. doi: 10.1002/tsm2.92

Jordan, M., Aagaard, P., and Herzog, W. (2015a). "A return to skiing envelope of function for anterior cruciate ligament reconstructed elite Alpine ski racers," in *Science and Skiing VI*, eds E. Muller, J. Kroll, S. Lindinger, J. Pfusterschmied, and T. Stoggle (Salzburg: Meyer & Meyer Sport), 187–195.

Jordan, M., Aagaard, P., and Herzog, W. (2015b). Lower limb asymmetry in mechanical muscle function: a comparison between ski racers with and without ACL reconstruction. *Scand. J. Med. Sci. Sports* 25, e301–e309. doi: 10.1111/sms.12314

Jordan, M., Aagaard, P., and Herzog, W. (2015c). Rapid hamstrings/quadriceps strength in ACL-reconstructed elite alpine ski racers. *Med. Sci. Sports Exerc.* 47, 109–119. doi: 10.1249/MSS.0000000000000375

Jordan, M., Aagaard, P., and Herzog, W. (2017a). Anterior cruciate ligament injury/reinjury in alpine ski racing: a narrative review. *Open access J. Sports Med.* 8, 71–83. doi: 10.2147/OAJSM.S106699

Jordan, M., Aagaard, P., and Herzog, W. (2017b). Asymmetry and thigh muscle coactivity in fatigued anterior cruciate ligament-reconstructed elite skiers. *Med. Sci. Sports Exerc.* 49, 11–20. doi: 10.1249/MSS.0000000000001076

Jordan, M., Aagaard, P., and Herzog, W. (2018). A comparison of lower limb stiffness and mechanical muscle function in ACL-reconstructed, elite, and adolescent alpine ski racers/ski cross athletes. *J. Sport Health Sci.* 7, 416–424. doi: 10.1016/j.jshs.2018.09.006

Jordan, M., Doyle-Baker, P., Heard, M., Aagaard, P., and Herzog, W. (2017c). A retrospective analysis of concurrent pathology in the ACL reconstructed knees of elite alpine ski racers. *Orthop. J. Sport. Med.* 5, 1–7. doi: 10.1177/2325967117714756

Konrath, J. M., Vertullo, C. J., Kennedy, B. A., Bush, H. S., Barrett, R. S., and Lloyd, D. G. (2016). Morphologic characteristics and strength of the hamstring muscles remain altered at 2 years after use of a hamstring tendon graft in anterior cruciate ligament reconstruction. *Am. J. Sports Med.* 44, 2589–2598. doi: 10.1177/0363546516651441

Linthorne, N. P. (2001). Analysis of standing vertical jumps using a force platform. *Am. J. Phys.* 69:1198. doi: 10.1119/1.1397460

Maffiuletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N., and Duchateau, J. (2016). Rate of force development: physiological and methodological considerations. *Eur. J. Appl. Physiol.* 116, 1091–1116. doi: 10.1007/s00421-016-3346-6

McPherson, A. L., Feller, J. A., Hewett, T. E., and Webster, K. E. (2019). Psychological readiness to return to sport is associated with second anterior cruciate ligament injuries. *Am. J. Sports Med.* 47, 857–862. doi: 10.1177/0363546518825258

Miles, J. J., King, E., Falvey, É. C., and Daniels, K. A. J. (2019). Patellar and hamstring autografts are associated with different jump task loading asymmetries after ACL reconstruction. *Scand. J. Med. Sci. Sports* 29, 1212–1222. doi: 10.1111/sms.13441

Myer, G. D., Paterno, M. V., Ford, K. R., Quatman, C. E., and Hewett, T. E. (2006). Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase. *J. Orthop. Sports Phys. Ther.* 36, 385–402. doi: 10.2519/jospt.2006.2222

Nagelli, C. V., and Hewett, T. E. (2016). Should return to sport be delayed until 2 years after anterior cruciate ligament reconstruction? Biological Functional Considerations. *Sport. Med.* 47, 221–232. doi: 10.1007/s40279-016-0584-z

Paterno, M. V., Rauh, M. J., Schmitt, L. C., Ford, K. R., and Hewett, T. E. (2012). Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin. J. Sport Med.* 22, 116–121. doi: 10.1097/JSM.0b013e318246ef9e

Paterno, M. V., Rauh, M. J., Schmitt, L. C., Ford, K. R., and Hewett, T. E. (2014). Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. *Am. J. Sports Med.* 42, 1567–1573. doi: 10.1177/0363546514530088

Pujol, N., Rousseaux Blanchi, M. P., and Chambat, P. (2007). The incidence of anterior cruciate ligament injuries among competitive alpine skiers: a 25-year investigation. *Am. J. Sports Med.* 35, 1070–1074. doi: 10.1177/0363546507301083

Spörri, J., Kröll, J., Amesberger, G., Blake, O. M., and Müller, E. (2012). Perceived key injury risk factors in World Cup alpine ski racing–an explorative qualitative study with expert stakeholders. *Br. J. Sports Med.* 46, 1059–1064. doi: 10.1136/bjsports-2012-091048

Wang, D., Chiaia, T., Cavanaugh, J. T., and Rodeo, S. A. (2019). Team approach: return to play after anterior cruciate ligament reconstruction. *JBJS Rev.* 7:e1. doi: 10.2106/JBJS.RVW.18.00003

Webster, K. E., and Hewett, T. E. (2019). What is the evidence for and validity of return-to-sport testing after anterior cruciate ligament reconstruction surgery? A Systematic Review and Meta-Analysis. *Sports Med.* 49, 917–929. doi: 10.1007/s40279-019-01093-x

Webster, K. E., McPherson, A. L., Hewett, T. E., and Feller, J. A. (2019). Factors associated with a return to preinjury level of sport performance after anterior cruciate ligament reconstruction surgery. *Am. J. Sports Med.* 47, 2557–2562. doi: 10.1177/0363546519865537

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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ORIGINAL RESEARCH
published: 06 March 2020
doi: 10.3389/fspor.2020.00011

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Prevention of Anterior Cruciate Ligament Injuries in Competitive Adolescent Alpine Skiers

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Edited by:
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Specialty section:
This article was submitted to
Sports Science, Technology and
Engineering,
a section of the journal
Frontiers in Sports and Active Living

Received: 31 August 2019
Accepted: 27 January 2020
Published: 06 March 2020

Citation:
Westin M, Harringe ML, Engström B, Alricsson M and Werner S (2020) Prevention of Anterior Cruciate Ligament Injuries in Competitive Adolescent Alpine Skiers. Front. Sports Act. Living 2:11. doi: 10.3389/fspor.2020.00011

Anterior cruciate ligament (ACL) injury is one of the most serious injuries among Swedish alpine ski high school students. An ACL injury forces the skier to stop skiing for several months, and some skiers even have to give up their skiing career. Therefore, an ACL injury prevention program might play an important role for alpine skiers. In the present study ski high school students have been followed in terms of ACL injuries during 1–2 ski seasons between 2006/2007 and 2012/2013. Alpine skiers studying at the Swedish ski high schools during the ski seasons 2011/2012 and 2012/2013 received a specific ACL injury prevention program ($n = 305$), while alpine skiers who attended a Swedish ski high school between the ski seasons 2006/2007 and 2010/2011 served as controls ($n = 431$). The prevention program was based on earlier studies and included indoor and outdoor exercises on snow focusing on core stability and neuromuscular control. Alpine skiing is an equilateral sport. Therefore, the goal of the prevention was to encourage the skiers to practice these exercises in order to perform equally good on both legs. The outcome measure consisted of the number and incidence of ACL injuries. The 2 years of prevention resulted in 12 ACL injuries (3.9%) compared with 35 ACL injuries during the control period (8.1%). The absolute risk rate showed a decreased incidence rate of −0.216 [CI −0.001–(−0.432)]/100 months attending a ski high school in favor of the intervention group. A prevention program focusing on the skier's ability to perform neuromuscular exercises equally good on both legs led to a reduction of ACL injuries.

Keywords: alpine skiing, adolescent, ACL injury, knee injuries, awareness program, risk factor

INTRODUCTION

Worldwide alpine skiing is a very popular winter sport (Hunter, 1999). It attracts both genders and different ages, and skiing performance depends on age and skiing level. Like other sports alpine skiing can, however, lead to severe injuries irrespective of skiing level (Westin et al., 2012; Bere et al., 2014; Stenroos and Handolin, 2014).

Several epidemiological studies in competitive alpine skiers have reported the knee to be the most frequently injured body part and anterior cruciate ligament (ACL) injury the most common diagnosis (Florenes et al., 2009; Bere et al., 2014; Stenroos and Handolin, 2014). From a 25-year follow-up of the French national ski team, Pujol et al. (2007) reported an incidence rate of 8.5 ACL injuries/100 ski seasons. An ACL injury is serious, and irrespective of gender it constitutes a risk for the skier's career as well as for early osteoarthritis (Lohmander et al., 2004; Nordenvall et al., 2014). These facts highlight the importance of ACL injury prevention.

In the epidemiological literature, van Mechelen's four steps model for developing a sport specific prevention program has been suggested (van Mechelen et al., 1992). The first step evaluates injury incidence and injury severity, the second step identifies injury mechanism and intrinsic as well as extrinsic injury risk factors, the third step consists of an intervention in terms of injury prevention based on steps one and two, and the fourth step evaluates the prevention strategies by repeating step one.

A number of both intrinsic and extrinsic risk factors for ACL injuries have been proposed (Smith et al., 2012a,b). However, to the best of our knowledge, only a few of these risk factors are sport specific for alpine skiing at the elite level. Raschner et al. (2012) found that impaired core strength was a critical factor for sustaining an ACL injury in young competitive ski racers. Westin et al. (2018) reported a higher risk to sustain an ACL injury in the left compared to the right knee. Bere et al. (2011a,b); Bere et al. (2013) studied the injury mechanism in World Cup skiers. From their video analysis of 20 ACL injuries they reported "slip and catch" to be the most common ACL injury mechanism (Bere et al., 2011a). The "slip and catch" mechanism means that the skier loose the pressure on the outer ski, while the inside edge of the outer ski is catching the snow and forces the knee into valgus and internal rotation. Moreover, Bere et al. (2011b) found that the majority of knee injuries occurred while skiing, and a technical as well as an inappropriate tactical mistake could lead to an ACL injury.

Still knowledge is sparse about alpine injury prevention, especially when it comes to adolescents. Changing the ski regulations by increasing the side cut radius and the ski length, Haaland et al. (2016) recently reported a reduction in the total injury incidence among skiers at the World Cup level. However, the side cut radius and the ski length change did not specifically influence the incidence of knee injuries (Haaland et al., 2016). For recreational skiers, there are two studies focusing on injury prevention by introducing a skiing education program (Ettlinger et al., 1995; Jlrgensen et al., 1998). Ettlinger et al. (1995) reported a reduction of 62% of serious knee sprains in skiers who had completed their "ACL-Awareness Program." Jlrgensen et al. (1998) reported a decreased injury risk by showing an instructional ski video.

In Sweden, about 700 skiers hold a FIS-license, and nearly 100% of these alpine skiers, aged 16–20 years, are studying at a Swedish ski high school. Approximately, 60 new alpine skiers are entering the ski high schools every year. The skiers can study 3–4 years at a Swedish ski high school. The admission to a Swedish ski high school is based on points from the ranking system of the International Ski Federation (FIS). Entering one of these ski high schools may lead to membership of the national team and thereby a possibility to reach the world class in alpine skiing.

Hewett et al. (2010) have reported that a side-to-side difference could increase the injury risk in either the dominant or the non-dominant leg. The individual skier might rely too much on his (or her) dominant leg, which may result in too high a load of the knee joint. Contrarily, less muscle strength, and impaired coordination of the non-dominant leg when compared with the dominant leg could also be an injury risk factor (Hewett et al., 2010). Alpine skiing is an equilateral sport where the skier needs to perform equally well when performing ski turns to the left as well as to the right. There are heavy physical demands in competitive alpine skiers in terms of rapid speeds and high external loads (Berg et al., 1995; Hintermeister et al., 1995). To meet these demands it is likely that the skier needs very good bilateral leg muscle strength symmetry (Neumayr et al., 2003). However, physical conditioning also includes other physical variables such as core stability, balance, and coordination (Hydren et al., 2013).

Since the season 2006/2007, Swedish ski high school students, age 16–20 years, have been prospectively followed with respect to physical performance and injuries. Risk profiles have been reported and risk factors concluded (Westin et al., 2018). The present study is the third step in the model by van Mechelen et al. (1992) where an ACL injury prevention program based on previous findings is implemented. The aim of the present investigation was to evaluate whether a sports specific prevention program including different exercises could reduce the incidence of ACL injuries in competitive adolescent alpine skiers.

MATERIALS AND METHODS

Study Design and Subjects

The present investigation is an ACL injury prevention study performed during a period of 21 months including two groups, an intervention group and a control group. The intervention group consisted of alpine skiers studying at a Swedish ski high school during the ski seasons 2011/2012 and 2012/2013. The control group consisted of 456 alpine skiers, who attended a ski high school between the seasons 2006/2007 and 2010/2011. Two ski seasons or 21 months attending a ski high school were the maximal time of exposure for a skier included in the present investigation. During this period the new changes of ski regulations by FIS were not yet implemented at the national level (Haaland et al., 2016). The reasons for using historical controls were 2-fold. Firstly, there would be a risk for crossover effects when some skiers performed a prevention program and other skiers did not. Secondly, in order to reduce the risk of a crossover effect a cluster randomization design would be appropriate, but the number of skiers would be a limited factor.

A total of 28 skiers were excluded from the study for two reasons: either they did not complete their studies at the school ($n = 21$) or they left the school due to earlier injuries ($n = 7$) (**Figure 1**).

At baseline the alpine skiers answered a questionnaire including questions such as how many years they had been skiing, at what age they started to participate in ski competitions, how important they found alpine skiing, and whether the skier had had any skiing related injuries that stopped him or her from participating in alpine skiing. The FIS ranking was obtained from the link of FIS, and the skier's FIS ranking when entering the study was used. Demographic data are presented in **Table 1**.

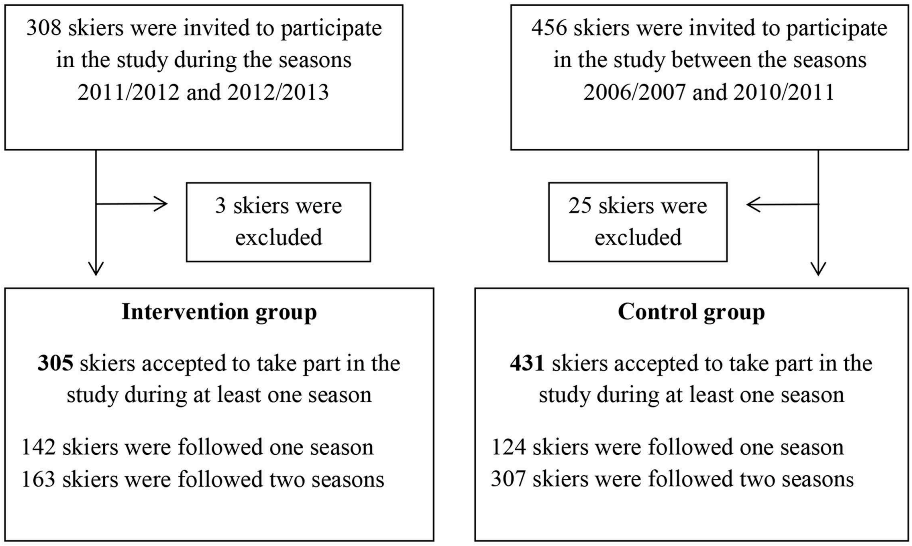

FIGURE 1 | Flowchart of the alpine skiers throughout the study period.

TABLE 1 | Specific characteristics of the alpine skiers at baseline.

	Intervention group (n = 305)	Control group (n = 431)
Gender	**Males (n = 148) Females (n = 157)**	**Males (n = 215) Females (n = 216)**
Age (year)[a]	17.1 ± 1.14	17.5 ± 1.23
Skiing experience (year)[a]	11.2 ± 2.31	11.3 ± 2.31
Competitive experience (year)[a]	8.6 ± 2.37	8.9 ± 2.29
FIS-rank SL (rank place)[b]	1,500 (27–5,261)	1,820 (14–5,895)
FIS-rank GS (rank place)[b]	1,831 (33–5,726)	2,102 (139–5,942)
Previous lower extremity injury	129 (42)	184 (43)
Previous ACL reconstructions[c]	23 (8) Males = 4 Females = 18	33 (8) Males = 4 Females = 27

There were no significant differences between the groups.
[a]Mean and standard deviation.
[b]Median and range.
[c]Number and percentage.
SL, slalom; GS, giant slalom.

TABLE 2 | Side distribution of ACL injuries during the study period.

	Intervention group		Control group	
	Males (n = 5)	**Females (n = 7)**	**Males (n = 14)**	**Females (n = 21)**
First time ACL injury (n, side)	4 (2 left, 2 right)	4 (2 left, 2 right)	11 (8 left, 3 right)	13 (9 left, 4 right)
ACL re-injury (n, side)	1 (left)	1 (left)	2 (left)	5 (4 left, 1 right)
ACL injury of the contralateral knee (n)		2	1	2
Third time ACL injury (n)				1

Intervention

ACL Injury Prevention Video

In collaboration with representatives from the Swedish Ski Federation and inspired by the Vermont Skiing Safety Research Group, an educational ACL injury prevention video was developed. The video was based on the injury profile (Westin et al., 2012) that identified intrinsic risk factors for ACL injuries in competitive adolescent alpine skiers (Westin et al., 2018) and their experience of having a safer/better ski turn to the right or to the left. The video was produced by two professional film producers.

The video (*https://www.youtube.com/watch?v=l-9CrG7lmAg&t=10s)* included information about ACL injuries in competitive alpine skiers and how to possibly avoid ACL injury situations while skiing. Additionally, the video consisted of three indoor and three outdoor exercises on snow focusing on core stability and neuromuscular control (Hewett et al., 2010). The Indoor exercises consisted of the one leg hop test for distance (Itoh et al., 1998), the square hop test (Itoh et al., 1998), and the single leg squat (Hydren et al., 2013). The outdoor exercises that were suggested by the Swedish Ski Federation consisted of the shuffle, the back and forth, and turns with lifted inner ski. The skiers were instructed to be aware of whether they were able to perform the exercises equally well on both legs and if they could perform equally well ski turns to the left as to the right.

First Year of Prevention

The prevention program was introduced in September 2011, and all ski coaches were taught how to implement the preventive strategies. The video was used as a support in order to educate the ski students about ACL injury prevention. They were instructed to watch the video every third week between September and November (preseason) and once each month between December and April (competition season). The education included information about identified risk factors for ACL injuries in alpine skiing and the importance of stimulating the skiers to regularly perform the suggested exercises. The coaches were informed that the ACL of the left leg was more often injured than that of the right leg. Therefore, the guidelines were to perform the exercises equally well on both legs.

Second Year of Prevention

Prior to the second year the test leader (MW) paid a visit at each ski high school in order to educate the new ski students and also to remind the other ski students as well as their coaches about the prevention program.

During the entire study period the test leader had monthly contact with the ski students as well their coaches. The reason for these contacts was to make sure that all ACL injuries were collected and to be informed about how the skiers complied with the suggested exercises. Their compliance with the training was collected using a questionnaire. At the end of the second year all coaches were reinvited to a meeting in order to secure that all ACL injuries had been recorded and reported to the main test leader.

Injury Report

All reported ACL injuries in the present study were total ACL ruptures, diagnosed by experienced orthopedic surgeons, and confirmed with MRI and/or arthroscopy.

Every month the test leader was in contact with the skiers by email and with the coaches by telephone asking about possible reinjuries or new ACL injuries. In case of an ACL injury the skier filled out a standardized injury form. Besides the date of injury and the injury mechanism, this form included questions about ski discipline, weather condition, visibility, slope conditions as well as temperature (Celsius degree) when the ACL injury occurred. In addition, this form included a question about physical fatigue and history of possible earlier injuries.

Statistical Analysis

Data is presented according to guidelines for reporting observational studies (Rothman, 2002). Descriptive statistics is presented for categorical data with median and range and for continuous data with mean and standard deviation. ACL injury prevalence was calculated as the number of ACL injuries divided by the total number of skiers, and a Chi-2 test was used to determine whether there was a significant difference with respect to ACL injuries between the groups. Time of exposure was calculated as the total number of months that a skier was attending a ski high school, and the ACL injury incidence (IR) was reported as the total number of ACL injuries per 100 months that a skier was attending a ski high school. A 95% confidence interval was estimated. The absolute rate reduction of the intervention was calculated as absolute incidence rate differences [IRD = IR (intervention group) – IR (control group)] with 95% confidence interval (Rothman, 2002). The time to the occurrence of an ACL injury between the groups was calculated and presented with the Kaplan–Meier survival curve. All *P*-values were two-tailed with $p < 0.05$ considered statistically significant. Data were analyzed using Statistica 12, StatSoft®, Inc. Tulsa OK, USA.

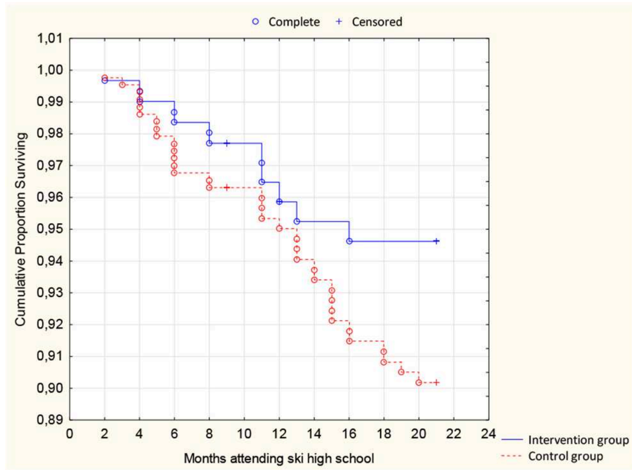

FIGURE 2 | Kaplan–Meier survival curve for ACL injuries in the intervention group and the control group.

RESULTS

During the intervention seasons 12 skiers (5 males, 7 females) sustained 12 complete ACL injuries. This resulted in a prevalence of 3.9% and an injury incidence of 0.26/100 months (95% CI 0.11–0.41) for a skier attending a ski high school. Eight of the injuries were first time ACL injuries, and two were re-injuries (**Table 2**).

During the control seasons there were 33 skiers (12 males, 21 females) that sustained a total of 35 complete ACL ruptures resulting in a prevalence of 8.1% and an injury incidence of 0.48/100 months (95% CI 0.32–0.64) for a skier attending a ski high school. Twenty-four of the ACL injuries were first time ACL injuries and seven were re-injuries (**Table 2**).

The absolute risk rate showed a decreased incidence rate of −0.216 (CI −0.001 to (−0.432)/100 months for a skier attending a ski high school in favor of the intervention group. A Hazard ratio of 0.56 (CI 0.29–1.08) was shown and reported according to the Kaplan–Meier survival curve (**Figure 2**). The number of ACL injuries in the intervention group was significantly reduced ($p = 0.03$).

Compliance With the Prevention Program

The ACL injury prevention program was included in the skiers' ordinary training. Out of the 305 skiers 94 (42%) answered the questionnaire about their compliance, and 75% reported that they had watched the video 1–5 times, 62% that their training had been focused on equilateral skiing, and 41% of the skiers had used the suggested exercises to find out whether their performance was equally well on both legs.

DISCUSSION

The overall aim of this investigation was to study whether a specific prevention program could reduce or prevent the number of ACL injuries in competitive adolescent alpine skiers.

The result showed a reduction of the incidence rate with −0.216 ACL injuries/100 months for a skier attending a ski high school. This means a reduction of 45% during the prevention period. Solely a few studies on ACL injury prevention in alpine skiing exist. In contrast to the present study Haaland et al. (2016) tried to prevent injuries by equipment changing focusing on intrinsic risk factors. To the best of our knowledge the present investigation is, however, the first one in adolescent alpine skiers at competitive level. Ettlinger et al. (1995) reported a decreased ACL injury rate as a result of a special educational program for ski instructors and ski patrollers in order to avoid ACL injury risk situations and also how to fall when off balance and how to stop after a fall. Like Ettlinger et al. (1995) the authors of the present study have tried to teach both the ski coaches and the alpine skiers to be aware of possible ACL injury risk situations. Awareness of certain risk situations may help to reduce the skier's technical mistake and thereby preventing an ACL injury (Bere et al., 2011b).

In a study of ACL injury risk factors we found that ACL injured alpine skiers showed an increased side-to-side difference when performing the one leg hop test for distance compared to the uninjured skiers. In the same investigation we also found that the skier's left knee was more injured than their right knee, which might at least to some extent, be due to this side-to-side difference (Westin et al., 2018). A recent publication about normative data when performing hop tests showed various results in terms of the best leg (left or right) for hop performance (Hildebrandt et al., 2015). When it comes to another hop test, the one leg counter movement jump, hop performance of the dominant leg was superior to the non-dominant leg (Hildebrandt et al., 2015). Alpine skiing is a multifactorial sport including a number of different physiological demands on the skier (Hydren et al., 2013). Furthermore, alpine skiing is an equilateral sport, meaning that the same physical demands are put on both legs. Therefore, the goal of the prevention program in the present investigation was to perform different types of exercises, indoors as well as outdoors on snow, with focus on how to perform equally well on the left and right legs. In female athletes it has been reported that those with a side-to-side asymmetry in terms of muscle strength are at a greater risk of an ACL injury than athletes without this asymmetry (Hewett et al., 2005) Whether this goes for male athletes, as well, is not known.

Moreover, Hewett et al. (2010) have pointed out the importance of a good neuromuscular balance between the quadriceps and hamstring muscles and between the dominant and non-dominant leg as well as a good postural control in order to prevent ACL injuries. These aspects may be of potential interest especially in an equilateral sport like alpine skiing. Therefore, in the present study, the prevention program was focused on each skier's awareness of his (or her) side-to-side ability when performing the suggested exercises, indoors as well as outdoors on snow. Thus, the goal was to perform equally well on both legs. Majority of earlier publications on ACL injury prevention are in team ball sports, such as soccer (Mandelbaum et al., 2005; Walden et al., 2012) and handball (Myklebust et al., 2003). These studies have been focused on neuromuscular warm-up programs which have led to a reduction of ACL injuries (Myklebust et al., 2003; Mandelbaum et al., 2005; Walden et al., 2012). Similar to these team ball studies we found that a training concept focusing on neuromuscular exercises can reduce the ACL incidence rate. As suggested by Finch (2006), the next step following this investigation should be to study motivators and barriers for the implementation of a prevention program. However, more studies specifically tailored for reducing ACL injuries in competitive adolescent alpine skiers are needed.

Strengths

A strength when using a prospective cohort design is that you are able to calculate the absolute risk. The absolute risk associated with exposure is of greater interest than the relative risk due to the statistical method. Another strength is that the preventive strategies implemented in young athletes may be more successful if both the skiers and their coaches are fully informed. In the present study, the coaches and the skiers were instructed to work together using an education program in order to reduce or prevent ACL injuries in competitive adolescent alpine skiers including exercises, both indoors and outdoors on snow, which also could be considered as strength of the study.

Limitations

Using historical controls may be seen as a study limitation, but the reasons were 2-fold. Firstly, the alpine ski students are regularly meeting each other at both national and international ski camps and ski competitions. Consequently, it was impossible to randomize some of the skiers to an intervention group and others to a control group without the risk of a crossover effect. Secondly, due to the limited number of alpine ski students in Sweden the use of historic controls was the way to being able to perform a prevention study of this type. More alpine ski students and/or a higher number of studied ski seasons might have been more appropriate. However, the present investigation was a cohort consisting of all Swedish alpine ski students with more than 200 students per year, and they are solely studying 3 or 4 years at a Swedish ski high school. Therefore, there would be huge logistical problems to increase the number of skiers and/or ski seasons.

Only 42% of the students in the intervention group replied on the compliance form, and it is therefore not trustworthy. Finch et al. (2011) concluded that a prevention program must be carried out regularly and be integrated with the normal sport specific training. In the present study both coaches and skiers were educated in the program, and the exercises were initially performed together with the coaches. Maybe that was the reason that the number of ACL injuries was reduced. From a psychological point of view, the close contact throughout the entire study period between the main test leader and the coaches and their alpine ski students could also have been the reason for the reduction of ACL injuries.

CONCLUSION

A prevention program of ACL injuries led to a 45% reduction of ACL injuries in Swedish alpine ski high school students. This indicates that an ACL injury prevention program consisting of neuromuscular exercises both indoors and outdoors on snow can prevent ACL injuries in competitive adolescent alpine skiers.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The present investigation was approved by the Regional Ethics Committee in Stockholm, Dnr 2006/833-31/1. Prior to entering the study all skiers were given both oral and written information. Participation was voluntary, and all skiers consented to participate.

AUTHOR CONTRIBUTIONS

MW conducted all data collecting. MW and MH conducted data analysis and graphical representation of the findings. All authors contributed to conception and design of the work, drafted it, revised it critically for important intellectual content, approved the final version of the manuscript, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

ACKNOWLEDGMENTS

We would like to thank the Swedish National Centre for Research in Sports, Stockholm Sweden and Stockholm County Council, Stockholm, Sweden for economical support. We also express sincere appreciation to all alpine skiers who volunteered to participate in this project.

REFERENCES

Bere, T., Florenes, T. W., Krosshaug, T., Koga, H., Nordsletten, L., Irving, C., et al. (2011a). Mechanisms of anterior cruciate ligament injury in World Cup alpine skiing: a systematic video analysis of 20 cases. *Am. J. Sports Med.* 39, 1421–1429. doi: 10.1177/0363546511405147

Bere, T., Florenes, T. W., Krosshaug, T., Nordsletten, L., and Bahr, R. (2011b). Events leading to anterior cruciate ligament injury in World Cup Alpine Skiing: a systematic video analysis of 20 cases. *Br. J. Sports Med.* 45, 1294–1302. doi: 10.1136/bjsports-2011-090517

Bere, T., Florenes, T. W., Nordsletten, L., and Bahr, R. (2014). Sex differences in the risk of injury in World Cup alpine skiers: a 6-year cohort study. *Br. J. Sports Med.* 48, 36–40. doi: 10.1136/bjsports-2013-092206

Bere, T., Mok, K. M., Koga, H., Krosshaug, T., Nordsletten, L., and Bahr, R. (2013). Kinematics of anterior cruciate ligament ruptures in World Cup alpine skiing: 2 case reports of the slip-catch mechanism. *Am. J. Sports Med.* 41, 1067–1073. doi: 10.1177/0363546513479341

Berg, H. E., Eiken, O., and Tesch, P. A. (1995). Involvement of eccentric muscle actions in giant slalom racing. *Med. Sci. Sports Exerc.* 27, 1666–1670. doi: 10.1249/00005768-199512000-00013

Ettlinger, C. F., Johnson, R. J., and Shealy, J. E. (1995). A method to help reduce the risk of serious knee sprains incurred in alpine skiing. *Am. J. Sports Med.* 23, 531–537. doi: 10.1177/036354659502300503

Finch, C. (2006). A new framework for research leading to sports injury prevention. *J. Sci. Med. Sport*. 9:3–9; discussion 10. doi: 10.1016/j.jsams.2006.02.009

Finch, C. F., White, P., Twomey, D., and Ullah, S. (2011). Implementing an exercise-training programme to prevent lower-limb injuries: considerations for the development of a randomised controlled trial intervention delivery plan. *Br. J. Sports Med.* 45, 791–796. doi: 10.1136/bjsm.2010.081406

Florenes, T. W., Bere, T., Nordsletten, L., Heir, S., and Bahr, R. (2009). Injuries among male and female World Cup alpine skiers. *Br. J. Sports Med.* 43, 973–978. doi: 10.1136/bjsm.2009.068759

Haaland, B., Steenstrup, S. E., Bere, T., Bahr, R., and Nordsletten, L. (2016). Injury rate and injury patterns in FIS World Cup Alpine skiing (2006–2015): have the new ski regulations made an impact? *Br. J. Sports Med.* 50, 32–36. doi: 10.1136/bjsports-2015-095467

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S. Jr, Colosimo, A. J., McLean, S. G., et al. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am. J. Sports Med.* 33, 492–501. doi: 10.1177/0363546504269591

Hewett, T. E., Ford, K. R., Hoogenboom, B. J., and Myer, G. D. (2010). Understanding and preventing acl injuries: current biomechanical and epidemiologic considerations - update 2010. *N. Am. J. Sports Phys. Ther.* 5, 234–251.

Hildebrandt, C., Muller, L., Zisch, B., Huber, R., Fink, C., and Raschner, C. (2015). Functional assessments for decision-making regarding return to sports following ACL reconstruction. Part I: development of a new test battery. *Knee Surg. Sports Traumatol. Arthrosc.* 23, 1273–1281. doi: 10.1007/s00167-015-3560-5

Hintermeister, R. A., O'Connor, D. D., Dillman, C. J., Suplizio, C. L., Lange, G. W., and Steadman, J. R. (1995). Muscle activity in slalom and giant slalom skiing. *Med. Sci. Sports Exerc.* 27, 315–322. doi: 10.1249/00005768-199503000-00005

Hunter, R. E. (1999). Skiing injuries. *Am. J. Sports Med.* 27, 381–389. doi: 10.1177/03635465990270032101

Hydren, J. R., Volek, J. S., Maresh, C. M., Comstock, B. A., and Kraemer, W. J. (2013). Review of strength and conditioning for alpine ski racing. *Strength Cond. J.* 35, 10–28. doi: 10.1519/SSC.0b013e31828238be

Itoh, H., Kurosaka, M., Yoshiya, S., Ichihashi, N., and Mizuno, K. (1998). Evaluation of functional deficits determined by four different hop tests in patients with anterior cruciate ligament deficiency. *Knee. Surg. Sports Traumatol. Arthrosc.* 6, 241–245. doi: 10.1007/s001670050106

Jlrgensen, U., Fredensborg, T., Haraszuk, J. P., and Crone, K. L. (1998). Reduction of injuries in downhill skiing by use of an instructional ski-video: a prospective randomised intervention study. *Knee. Surg. Sports Traumatol. Arthrosc.* 6, 194–200. doi: 10.1007/s001670050098

Lohmander, L. S., Ostenberg, A., Englund, M., and Roos, H. (2004). High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum.* 50, 3145–3152. doi: 10.1002/art.20589

Mandelbaum, B. R., Silvers, H. J., Watanabe, D. S., Knarr, J. F., Thomas, S. D., Griffin, L. Y., et al. (2005). Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *Am. J. Sports Med.* 33, 1003–1010. doi: 10.1177/0363546504272261

Myklebust, G., Engebretsen, L., Braekken, I. H., Skjolberg, A., Olsen, O. E., and Bahr, R. (2003). Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. *Clin. J. Sport Med.* 13, 71–78. doi: 10.1097/00042752-200303000-00002

Neumayr, G., Hoertnagl, H., Pfister, R., Koller, A., Eibl, G., and Raas, E. (2003). Physical and physiological factors associated with success in professional alpine skiing. *Int. J. Sports Med.* 24, 571–575. doi: 10.1055/s-2003-43270

Nordenvall, R., Bahmanyar, S., Adami, J., Mattila, V. M., and Fellander-Tsai, L. (2014). Cruciate ligament reconstruction and risk of knee osteoarthritis: the association between cruciate ligament injury and post-traumatic osteoarthritis. a population based nationwide study in Sweden, 1987-2009. *PLoS ONE.* 9:e104681. doi: 10.1371/journal.pone.0104681

Pujol, N., Blanchi, M. P., and Chambat, P. (2007). The incidence of anterior cruciate ligament injuries among competitive Alpine skiers: a 25-year investigation. *Am. J. Sports Med.* 35, 1070–1074. doi: 10.1177/0363546507301083

Raschner, C., Platzer, H. P., Patterson, C., Werner, I., Huber, R., and Hildebrandt, C. (2012). The relationship between ACL injuries and physical fitness in young competitive ski racers: a 10-year longitudinal study. *Br. J. Sports Med.* 46, 1065–1071. doi: 10.1136/bjsports-2012-091050

Rothman, J. K. (2002). *Epidemiology- An Introduction*. New York, NY: Oxford.

Smith, H. C., Vacek, P., Johnson, R. J., Slauterbeck, J. R., Hashemi, J., Shultz, S., et al. (2012a). Risk factors for anterior cruciate ligament injury: a review of the literature - part 1: neuromuscular and anatomic risk. *Sports Health.* 4, 69–78. doi: 10.1177/1941738111428281

Smith, H. C., Vacek, P., Johnson, R. J., Slauterbeck, J. R., Hashemi, J., Shultz, S., et al. (2012b). Risk factors for anterior cruciate ligament injury: a review of the literature-part 2: hormonal, genetic, cognitive function, previous injury, and extrinsic risk factors. *Sports Health.* 4, 155–161. doi: 10.1177/1941738111428282

Stenroos, A. J., and Handolin, L. E. (2014). Alpine skiing injuries in Finland - a two-year retrospective study based on a questionnaire among Ski racers. *BMC Sports Sci. Med. Rehabil.* 6:9. doi: 10.1186/2052-1847-6-9

van Mechelen, W., Hlobil, H., and Kemper, H. C. (1992). Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. *Sports Med.* 14, 82–99. doi: 10.2165/00007256-199214020-00002

Walden, M., Atroshi, I., Magnusson, H., Wagner, P., and Hagglund, M. (2012). Prevention of acute knee injuries in adolescent female football players: cluster randomised controlled trial. *BMJ.* 344:e3042. doi: 10.1136/bmj.e3042

Westin, M., Alricsson, M., and Werner, S. (2012). Injury profile of competitive alpine skiers: a five-year cohort study. *Knee. Surg. Sports Traumatol. Arthrosc.* 20, 1175–1181. doi: 10.1007/s00167-012-1921-x

Westin, M., Harringe, M. L., Engstrom, B., Alricsson, M., and Werner, S. (2018). Risk Factors for anterior cruciate ligament injury in competitive adolescent alpine skiers. *Orthop. J. Sports Med.* 6:2325967118766830. doi: 10.1177/2325967118766830

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.

ORIGINAL RESEARCH
published: 27 March 2020
doi: 10.3389/fspor.2020.00025

Alpine Ski Motion Characteristics in Slalom

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Important insight into ski function, and ultimately skier technique and tactics, can be gained by studying how measured ski trajectories compare to predictions based on theoretical models of ski-snow interaction mechanics. The aim of this investigation was to use a 3D kinematic data set collected on highly-skilled skiers during slalom race simulations to quantify ski motion characteristics and to compare these measures with theoretical predictions based primarily on ski geometrical characteristics. For slalom turns on moderate steepness (19°), ski edging angles reached maximum values of 65.7 ± 1.7° and 71.0 ± 1.9° for 10 and 13 m gate spacings. Turn radii reached minimum values of 3.96 ± 0.23 and 4.94 ± 0.59 m for the 10 and 13 m courses. These values were in good agreement with theoretical predictions by Howe (2001) of turn radius based on edging angle. Other results of the study support recent developments in understanding of the role which the ski shovel plays in groove formation during carving, and also point to the need for further study of how ski geometrical and physical characteristics interact to determine the ski's trajectory, particularly at low edge angles. These results have important implications for understanding the consequences that ski design can have for skier technique and tactics in competitive slalom skiing.

Keywords: alpine skiing, alpine ski, ski characteristics, ski motion, ski-snow interaction, ski mechanics

Edited by:
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Specialty section:
This article was submitted to Sports Science, Technology and Engineering, a section of the journal Frontiers in Sports and Active Living

Received: *11 October 2019*
Accepted: *04 March 2020*
Published: *27 March 2020*

Citation:
Reid RC, Haugen P, Gilgien M, Kipp RW and Smith GA (2020) Alpine Ski Motion Characteristics in Slalom. Front. Sports Act. Living 2:25. doi: 10.3389/fspor.2020.00025

INTRODUCTION

Turning technique is undoubtedly an important performance variable in alpine ski racing as can readily be ascertained by the attention it receives from coaches and athletes as well as from the sheer volume of scientific, professional, and lay publications addressing the topic. To turn, a skier manipulates the orientation and loading pattern of skis to generate a reaction force from the snow surface that allows redirection of trajectory and regulation of speed. Grasping the mechanics of how the ski interacts with the snow surface thus lays the foundation for understanding skier actions. Equally important, enhancing knowledge of ski-snow interaction mechanics is essential for the development of appropriate competition equipment regulations (Spörri et al., 2016a) to reduce the high injury rates seen in alpine ski racing (Florenes et al., 2009, 2012; Haaland et al., 2015). Theoretical models of ski-snow interaction mechanics have been described and tested using numerical simulations and physical models. However, there is a lack of empirical evidence validating these models under competitive conditions. And while several studies have investigated the effect of changes in ski geometry on injury risk, they have considered the athlete as a point mass (Gilgien et al., 2013, 2015c), relating equipment characteristics to gross biomechanical variables (i.e., speed, forces, trajectory) rather than the ski-snow interaction itself (Gilgien et al., 2016, 2018; Kröll et al., 2016a,b). To further our understanding of how ski characteristics influence the ski-snow interaction, the aim of this investigation was to use a 3D kinematic data set collected on highly-skilled skiers during slalom race simulations to quantify ski motion characteristics and to compare these measures with theoretical predictions.

LITERATURE REVIEW

Alpine Ski Characteristics

Alpine skis have geometrical and physical properties which influence how they interact with the snow surface. They have smooth, curved edge profiles referred to as sidecut, the amount of which varies depending on the type of ski. Two parameters are used to describe a ski's sidecut: Side camber and sidecut radius. Side camber (*SC*) is the distance between the ski at the narrowest part (waist) and a straight line between the widest points at the tail and shovel (Hirano and Tada, 1996; Kaps et al., 2001; Lind and Sanders, 2004; Federolf et al., 2010b). The sidecut radius (R_{SC}) refers to the radius of a circle that intersects the side of the ski at the shovel, waist, and tail points while the ski is pressed flat on a planar surface (Kaps et al., 2001; Lind and Sanders, 2004). Primarily a function of the ski's width, thickness, and the materials used in its construction, a ski's flexural stiffness varies along its length (Howe, 2001; Lind and Sanders, 2004; Federolf et al., 2010b). The ski is in addition pre-stressed during construction as its layers are glued together causing the unloaded ski to take on a bent shape that is referred to as camber (Howe, 2001; Lind and Sanders, 2004; Federolf et al., 2010b). Together with the flexural stiffness distribution, the ski's camber affects the distribution of pressure under the ski's running surface when it is loaded. Torsional stiffness refers to the ski's ability to resist deformation about its longitudinal axis (Howe, 2001; Lind and Sanders, 2004) and, together with flexural stiffness, plays an important role in determining how aggressively the ski tip and tail interact with the snow when the ski is edged and loaded (LeMaster, 1999; Zorko et al., 2015).

Ski Reference Systems

To understand a ski's function, it is important to quantify its motion and orientation relative to the snow surface. Toward this end, Lieu (1982) and Lieu and Mote (1985) introduced a reference system to quantify a ski's orientation and the resulting angles with the snow surface (**Figure 1**). Originating at the ski center point, the **EFG** coordinate system defines the ski's position and orientation. **E** is oriented parallel to the ski's longitudinal axis, while **F** and **G** are directed lateral and normal to the ski sole surface, respectively.

Two angles between the ski and the snow surface are of particular importance to the ski's function. θ is the "edge angle" between the plane of the local snow surface and the running surface of the ski and describes to what degree the ski is tilted "on edge" relative to the local snow surface. The ski's "attack angle" (ϕ) is the angle between the ski's longitudinal axis **E** and the center point's velocity vector **V** in a plane parallel to the local snow surface. The attack angle describes to what degree the ski's longitudinal axis is oriented along it's direction of motion, an important factor influencing the nature of the ski-snow interaction. While ϕ represents the whole ski angle of attack, the local angle of attack at each position along the ski's length varies according to the ski's geometrical properties, its deformed shape under edging and loading, and its rotational and translational motion relative to the snow surface (Hirano and Tada, 1996; LeMaster, 1999; Tada and Hirano, 2002; Hirano, 2006; Spörri et al., 2016b). There are typically larger local attack angles on the ski forebody than on the ski afterbody, a fact that plays an important role in the ski's turning behavior.

Skidding and Carving

When describing a ski's motion along the snow surface, two processes are generally recognized. During carving, a point along the ski's edge follows in the path of proceeding ski segments with minimal or no lateral displacement relative to the track (Lieu, 1982; Lieu and Mote, 1985; Brown and Outwater, 1989; Renshaw and Mote, 1989). In contrast, a ski that is sliding sideways across the snow surface as it moves forward is said to be skidding (LeMaster, 1999). A point on the ski's edge that is skidding does not follow in the path of proceeding points but rather shears through new snow as it moves across the snow surface (Lieu, 1982; Lieu and Mote, 1985; Brown and Outwater, 1989; Renshaw and Mote, 1989). In practitioner terms, an entire ski is often described as either skidding or carving. However, such a classification is an oversimplification as both carving and skidding may occur at the same time along different segments of the ski's length.

Lieu (Lieu, 1982) and Lieu and Mote (1985) modeled numerically the motion of skis through constant radius, constant speed turns and studied the effect of decreasing the ski angle of attack on ski motion. They found that at attack angles of ~11 degrees and greater, all points along the ski's length were in a skid mode. As the angle of attack was lowered to below 9 degrees, Lieu and Mote found that carving initiated at the tail of the ski. Further decreases in attack angle were associated with increased portions of the ski afterbody transitioning to carving. However, even in advanced carving stages, Lieu and Mote found that carving was limited to the ski's afterbody.

Carving and Groove Formation

Lieu and Mote's (1985) findings are important in that they help to explain the mechanics of how a carving ski forms the groove in which the afterbody of the ski will ride. As the tip of an edged and loaded ski passes over a point on the snow surface, the first portion of the ski to contact the snow is often relatively soft in torsion and flexion and not heavily loaded. Accordingly, this portion of the ski may not penetrate the snow, but instead skid across the surface, vibrating in both flexion and torsion. With each passing point of the ski, stiffer portions of the forebody meet the snow and eventually enough pressure develops to push the ski into the snow surface. From this point on, the ski continues to penetrate deeper into the snow with each subsequent passing point, generating a groove (Tatsuno et al., 2009; Federolf et al., 2010b; Heinrich et al., 2010). The rising pressure increases the penetration depth and progressively compresses snow into the

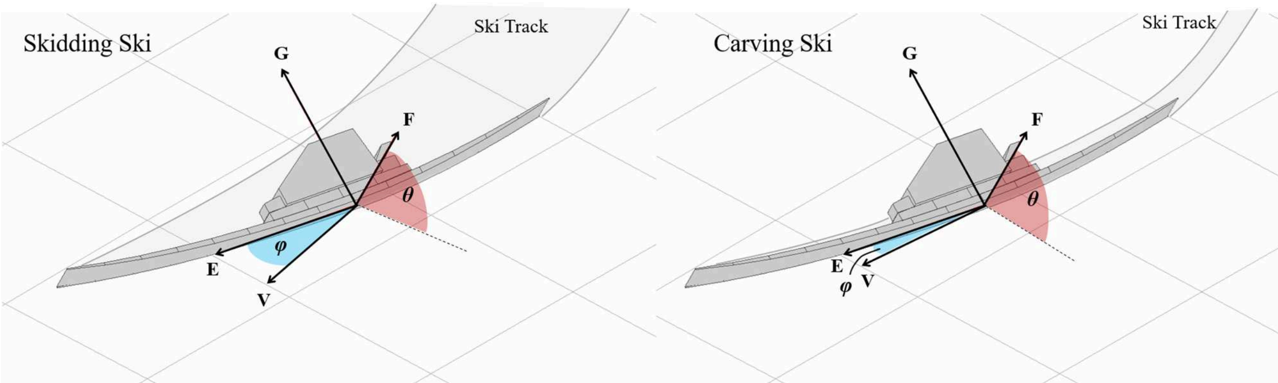

FIGURE 1 | The ski edge angle (θ) and attack angle (ϕ) as defined by Lieu and Mote (1985). θ is the edge angle between the plane of the local snow surface and the running surface of the ski. The ski's angle of attack (ϕ) is the angle between the ski's longitudinal axis (E) and the center point's velocity vector (V) projected to a plane parallel to the local snow surface. The left panel presents a skidding ski with a relatively large attack angle, scraping a wide track into the snow surface. For contrast, the right panel presents a carving ski with a small angle of attack, leaving a narrow track in the snow.

groove sidewall, both of which improve the groove's resistance to shear in preparation for the high forces which will occur as the boot passes (Mössner et al., 2006; Tatsuno et al., 2009). From the point of maximal pressure, the remainder of the ski is relatively unloaded in penetration and rides in the groove generated by the passage of the forebody. Seen in this way, the ski forebody does not ever carve—in a very strict sense of the word—since points along the forebody edge will trace their own trajectory, cutting new snow in the process, as has been predicted in both the research literature (Lieu, 1982; Lieu and Mote, 1985; Sahashi and Ichino, 1998; Casolo and Lorenzi, 2001) and practitioner textbooks (Joubert, 1980).

Ski Trajectory

Early attempts to model the carving ski's trajectory were based solely on the geometrical properties of the ski and the resulting shape of the deformed ski as it is edged and loaded onto the snow surface. For rigid, planar snow surfaces, Howe (2001) proposed Equation 1 that relates the deformed ski's radius of curvature (R_T) to its edge angle (θ) and sidecut radius (R_{SC}):

$$R_T = R_{SC} \cos\theta \tag{1}$$

Increasing the degree to which the ski is deformed onto the snow surface is expected to reduce R_T, tightening the ski's turn trajectory. As Equation 1 suggests, one way of doing this is to increase the edging angle. As the ski is turned more onto edge, it will need to bend more to come into contact with the snow surface resulting in greater deformation and a shorter effective turn radius. This phenomenon has been demonstrated in a number of studies (e.g., Heinririch et al., 2006; Federolf et al., 2010a; Mossner et al., 2010). Along similar lines, increasing the ski's sidecut has also been found to amplify the ski's bending deformation, resulting in a decreased R_T (Hirano and Tada, 1996).

Despite this empirical evidence, Equation 1 is an oversimplification in several important ways. First, while the snow surface may at times be very hard, it is in reality never perfectly rigid. As previously described, skis penetrate into the snow surface, the depth of which is dependent upon the loading force, the snow's resistance to penetration, and the edging angle (Lieu and Mote, 1985; Brown and Outwater, 1989; Tada and Hirano, 2002; Federolf, 2005). This increases the ski's deformation and should therefore reduce R_T to a value lower than that estimated by Equation 1 (Howe, 2001; Kaps et al., 2001). This lead Howe to propose Equation 2 to account for non-rigid snow surfaces where C is the contact length, SC is the side camber, and D_P is the penetration depth:

$$R_T = \frac{C^2}{8\left[(SC/\cos\theta) + D_P \sin\theta\right]} \tag{2}$$

A second limitation of both Equations 1 and 2 is that they are based on the assumption that the entire length of the ski edge is in contact with the snow and carving. In reality however, certain portions of the ski will often alternate between carving and skidding modes depending on the balance between the local running surface pressure, the local edge angle and the local snow's shear strength.

Several researchers have recently reported experimental evidence indicating that carving skis do not follow exactly in the trajectory defined by the shape of the deflected edge on the snow surface, as both Equations 1 and 2 assume. In a study of elite skiers in giant slalom, Wimmer (2001) found only modest correlations ($r = 0.39$–0.57) between ski turn radius, as derived from reconstructed ski trajectories, and that calculated using Equation 1. He reported particularly large differences between reconstructed and predicted turn radii around turn transitions where the actual ski turn radius approached large values and the calculated turn radius approached a limit of R_{SC}.

Kagawa et al. (2009), Tatsuno et al. (2009), and Yoneyama et al. (2008) measured ski deformations in carved turns using instrumented skis. Although they did not measure the ski's trajectory, they estimated that the actual ski turn radius was approximately twice that of the radius defined by the deformed ski edge. This they related to the mechanics of groove formation during carving and the idea that the ski forebody does not carve as it plows through the snow, establishing a groove.

Federolf (2005) and Federolf et al. (2010b) geodetically surveyed the track left in the snow by a carving ski in a giant slalom turn and compared the ski's actual turn radius to predictions using Howe's (2001) equation that accounts for snow penetration (Equation 2). He found that predicted turn radii based on the expected shape of the deformed ski underestimated actual measures and showed how the forebody of the ski will be deformed to a greater extent than can be accounted for in a carving ski's trajectory, particularly at higher edge angles. Using a Finite Element simulation of a carving ski that incorporated the mechanics of groove formation, Federolf et al. (2010a) found that Howe's equation agreed well with simulation results for low edge angles (<40 degrees) but that at high edge angles Howe's equation underestimated the ski's simulated turn radius.

That the carving ski's trajectory does not necessarily correspond to its deformed shape on the snow surface challenges our understanding—as both researchers and practitioners—of how the ski interacts with the snow surface. The purpose of this investigation was therefore to determine how well ski motion characteristics, which were measured in a previous kinematic study of skier technique, correspond to predictions of ski motion based on our theoretical understanding of ski snow interaction mechanics. In particular, our aims were to (1) examine how well-measures of local ski attack angles corresponded to Lieu and Mote's (Lieu, 1982; Lieu and Mote, 1985) prediction that carving is limited to the aft portion of the ski and (2) determine how well Howe's (2001) equation for turn radius based on ski geometry and edge angle (Equation 1) predicts actual ski trajectory measures.

METHODS

Six male members of the Norwegian national team (aged 17–20) volunteered to participate in a kinematic study of skier technique in April, 2006 (Reid et al., 2009; Reid, 2010; Federolf et al., 2012). This study was conducted in accordance with the Declaration of Helsinki and Norwegian law and was approved by the Norwegian Center for Research Data. All subjects gave their written informed consent prior to participation.

Skier kinematics were captured over two complete turns during slalom race simulations using a DLT-based method and four panning cameras (50 Hz) (Reid et al., 2009; Reid, 2010; Federolf et al., 2012). Skiers completed three runs on each of two courses set rhythmically with 10 and 13 m linear gate distances on even, moderately steep terrain (19° slope) and hard, compact snow conditions. The fastest run from each course was selected for further analysis giving a total of 24 analyzed turns for this investigation, 12 on each course. Two hundred and eight control points were positioned so as to surround the two turns of interest, creating a calibration volume of ∼50 × 10 × 2 m (**Figure 2**). The control points, gates, and snow surface were geodetically surveyed using a theodolite. Camera images were individually calibrated using an average of 29 control points per frame and were synchronized after recording using an adaptation of the software genlock method (Pourcelot et al., 2000) that accommodates panning cameras. The ski tip (*TIP*), tail (*TAIL*), and ankle joint center (*AJC*) were manually digitized and reconstructed position data were filtered using a zero-lag, 2nd order, low-pass Butterworth filter and 20 padding points. The Challis residual autocorrelation algorithm (Challis, 1999) was used to individually determine the appropriate cut-off frequencies for each point (*TIP*, 9 Hz; *TAIL*, 8 Hz; *AJC*, 9 Hz).

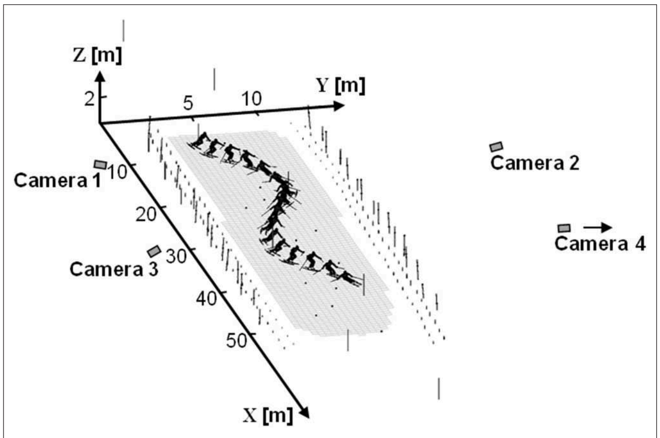

FIGURE 2 | A graphical reconstruction of the experimental set-up. Control point positions are indicated by the small points and poles. Note that camera 4 was actually placed 30 m further to the right as seen from this perspective.

One limitation of this approach is the error associated with manual digitization. Several measures were therefore taken to minimize digitization error including an extensive training program with feedback; the use of photographs of equipment to assist point identification; and the identification of outliers in the data set for double-checking and correction. Measurement accuracy was assessed using control points positioned on the snow surface close to the skier's trajectory but which were removed from the calibration sequence for the purpose of accuracy assessment. A total of 980 so-called "*non*-control point" reconstructions were assessed across all 12 of the analyzed trials. *Non*-control point root mean squared error (RMSE) was 4, 5, and 2 mm in the **X**, **Y**, and **Z** dimensions, respectively. Pooled standard deviations of segment lengths were used to assess digitizer reliability. Over the 12 analyzed trials, the skis were reconstructed 2,170 times with a pooled standard deviation for the ski running surface length of 11 mm.

The *TIP*, *TAIL*, and *AJC* position data were fit with a 15 segment model of a 14 m sidecut radius ski. To accomplish this, a third point on the ski sole (*MID*) was defined as the point between 16 and 19 cm below *AJC* in the direction perpendicular to the *TIP*–*TAIL* vector, assuming that the ski sole to foot sole distance was close to the maximum allowable in competition (10 cm in 2006) and that the foot sole to *AJC* distance was between 6 and 9 cm (**Figure 3**). The actual distance was chosen for each athlete individually so as to obtain 0 mm ski flexural deformation at turn transitions. Subsequent to determining *MID*, the ski midline was

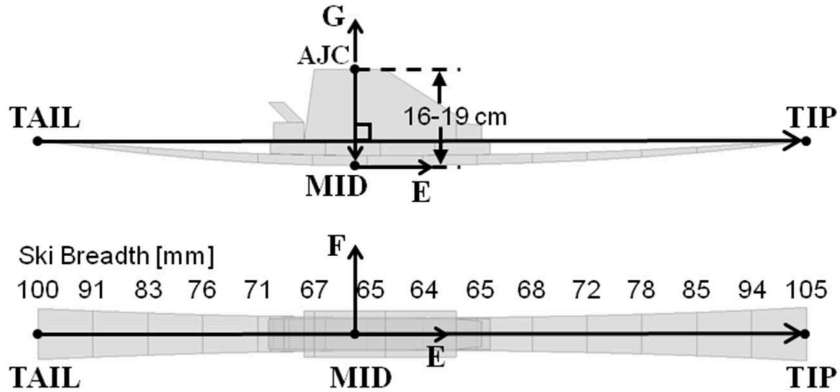

FIGURE 3 | The 15 segment ski model fitted to *TIP*, *TAIL*, and *AJC*. *MID* was defined as the point along the ski sole 16–19 cm below *AJC*, in the direction perpendicular to the *TIP-TAIL* vector.

then approximated by fitting *TIP*, *MID*, and *TAIL* with a cubic spline function, constructing points at 15 evenly spaced intervals. Positions along the ski's edges were then approximated using the average sidecut profile of 11 slalom skis. The reconstructed ski running surface length had a pooled standard deviation of 11 mm ($n = 2{,}170$ measurements taken over 12 trials).

In order to calculate ski motion characteristics, a smooth snow surface model with continuous first- and second-order derivatives was generated based on the Delaunay triangulation of the geodetically captured snow points (Gilgien et al., 2015a,b). The ski edge angle (θ) was defined in accordance with Lieu (1982) as the angle between the plane of the local snow surface and the running surface of the ski. θ is however probably most appropriately described as a rough estimate of the ski edge angle. The actual edge angle can be expected to differ somewhat from this estimate depending on the individual's binding and boot set-up (Müller et al., 1998). In addition, the edge angle is likely to vary along the ski's length due to ski flexion and torsion deformations whose measurement was beyond the resolution of the method employed in this investigation. Complicating matters further is the fact that the exact nature of the local snow surface was not precisely known and can be expected to progressively change with each passing skier as the snow is scraped and deformed.

The ski attack angle (ϕ), defined as the angle between the ski's longitudinal axis and the center point's velocity vector (Lieu, 1982), was quantified to describe the degree of skidding and carving. Local ski attack angles ϕ_E for points along the outside ski's interacting edge were calculated in a similar manner for comparison with Lieu and Mote's predictions of ski motion (Lieu, 1982; Lieu and Mote, 1985).

The radius of curvature of the ski center point's trajectory (R_{SKI}) at time point index i, parallel to the least squares plane of the snow surface, was calculated by determining the radius of the circle fitting the center point's positions at time point index i, $i-3$, and $i+3$. As the actual penetration depth was not measured, the simpler Howe (2001) equation (Equation 1) was used to predict turn radius (R_{HOWE}) based on the ski's sidecut radius and the measured edge angle. These theoretical turn radii were compared with those directly measured during slalom turns on each course.

RESULTS

Figure 4 shows the outside ski attack angle, edge angle, and turn radius for sample turns on the 10 and 13 m courses. At the start of the turn cycle, the new outside ski was already slightly edged to on average 5.1 ± 4.6 and 4.5 ± 5.1 degrees on the 10 and 13 m courses, respectively. On the 10 m course, edge angle progressively increased through the first half of the turn, reaching an average maximum angle of 65.7 ± 1.7 degrees just after gate passage. On the 13 m course, there was an initial rapid rise in edge angle followed by a period of more gradual increase, reaching maximum angles of 70.2 ± 1.3 degrees at approximately gate passage. Edge angle then declined rapidly during turn completion for both gate distances.

The outside ski had on average a positive attack angle of 3.1 ± 2.4 and 0.5 ± 2.4 degrees at the transition between turns on the 10 and 13 m courses, respectively, indicating that the skis were already being oriented for the upcoming turn during the completion of the previous turn. Attack angles rose rapidly during turn initiation, reaching average maximums of 15.1 ± 5.3 and 12.1 ± 4.9 degrees early in the turn for the 10 and 13 m courses, respectively. During the first half of the turn cycle, attack angles were greater on the 10 m course, in particular from 10 to 45 % of the turn cycle, indicating that there was a greater degree of skidding used on the 10 m course, on average. There was, however, a substantial amount of individual variation on both courses during this part of the turn with some turns being carved and some skidded. The outside ski then shifted to carving by about gate passage with all turns on both courses being completed at attack angles below 4 degrees.

To allow comparison with Lieu and Mote's predictions (Lieu, 1982; Lieu and Mote, 1985), **Figure 5** presents the local ski attack angle (ϕ_E) data averaged according to position along the ski's longitudinal axis and whole ski attack angle (ϕ) for the steering phase of the turn cycle. To help visualize the meaning of the local attack angle data, sample graphics were generated showing ski edge point trajectories during the transition from skidding to carving. The dashed and solid lines indicate ski forebody and rearbody point trajectories, respectively.

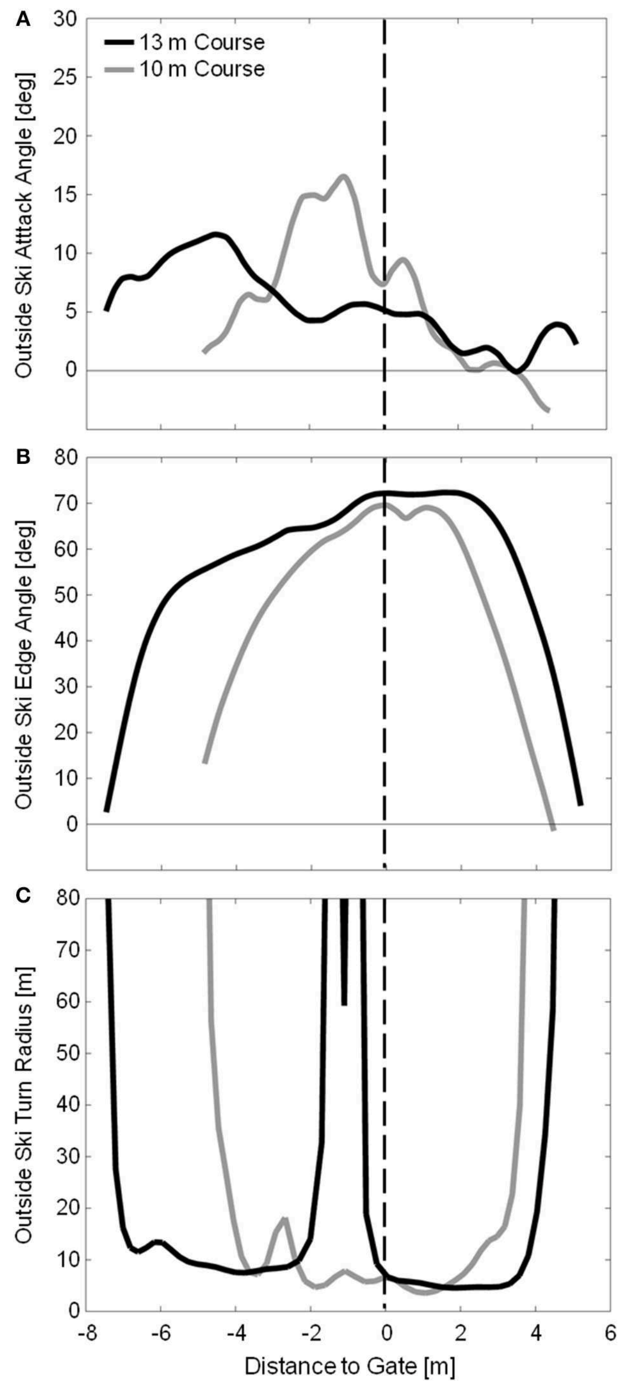

FIGURE 4 | Measured outside ski attack angle **(A)**, edge angle **(B)**, and turn radius **(C)** for sample turns from the 10 and 13 m courses in gray and black, respectively. Due to the different course setting, the data from the two courses are coordinated using the gate as a common point, and presenting the X axis as distance to gate. Gate passage is indicated by the vertical dashed line. It is relevant to note that turns on the 13 m course start much higher up on the slope relative to the gate than on the 10 m course.

Minimum outside ski turn radius measurements were slightly longer on the 13 m course (4.94 ± 0.59 m) than on the 10 m course (3.96 ± 0.23 m) despite the higher maximum edge angles observed on the 13 m course. In contrast to the 10 m course, large fluctuations in R_{SKI} were observed during the early to mid-portion of the turn on the 13 m course, as exemplified in **Figure 4C**. **Figure 6** compares the measured turn radius (R_{SKI}) to that predicted using Howe's (2001) equation (R_{HOWE}) for time points where the ski was considered to be carving, defined as $\phi < 5$ degrees. RMSE between the measured (R_{SKI}) and predicted (R_{HOWE}) turn radii was 27.2 and 44.5 m for the 10 and 13 m courses, respectively. However, prediction error was much higher for edge angles below 45 degrees (42.0 and 71.5 m RMSE for the 10 and 13 m courses, respectively) than for edge angles above 45 degrees (2.5 and 6.4 m RMSE for the 10 and 13 m courses, respectively).

DISCUSSION

Skidding and Carving

There was a slightly greater degree of skidding on the 10 m course, primarily in the first portion of the turn. However, with average maximum attack angles of 15 and 12 degrees seen on the 10 and 13 m courses, respectively, the skidding in this study is perhaps best described as moderate compared to what can often be observed in typical competition conditions. That skiers used some skidding in this investigation is not surprising considering that the experimental set-up was on moderately steep terrain where skidding can be used to regulate speed.

In the comparison with Lieu and Mote's predictions (Lieu, 1982; Lieu and Mote, 1985) (**Figure 5**), some variability in local ski attack angle patterns was evident, likely due to variation in the mechanical and geometrical properties of the skis used by the athletes as well as irregularities in the ski's motion. In general, however, local attack angles were high along the entire ski when whole ski attack angles were greater than about 15 degrees, indicating that skidding processes dominated. Below this level, local attack angles in the aft-most ski segments reduced while those of the forebody segments remained elevated. Local attack angles of the aft-most segments reached 2 to 5 degrees as whole ski attack angles approached 8 degrees, indicating that these points began carving, in good accordance with Lieu and Mote's results. Further decreases in the whole ski attack angle were associated with increasing numbers of tail segments carving, along with the reduction of forebody segment attack angles. The ski reached an advanced carving stage at whole ski attack angles of ∼3 degrees, although local forebody segment attack angles remained slightly elevated, indicating that this part of the ski was still machining new snow, also in good accordance with Lieu and Mote's work as well as Tatsuno's (2009), Federolf's (2005), and Federolf et al. (2010b) descriptions of ski shovel function.

Ski Trajectory

The outside ski experienced high intensity turning over the majority of the turn cycle, in some instances starting prior to the transition between turns. For portions of the turn cycle where the ski was carving and the edge angle was relatively high ($\theta > 45$ degrees, see **Figure 6**), Howe's equation (Equation 1) performed surprisingly well in predicting the actual ski turn radius, considering the simplicity of the equation and

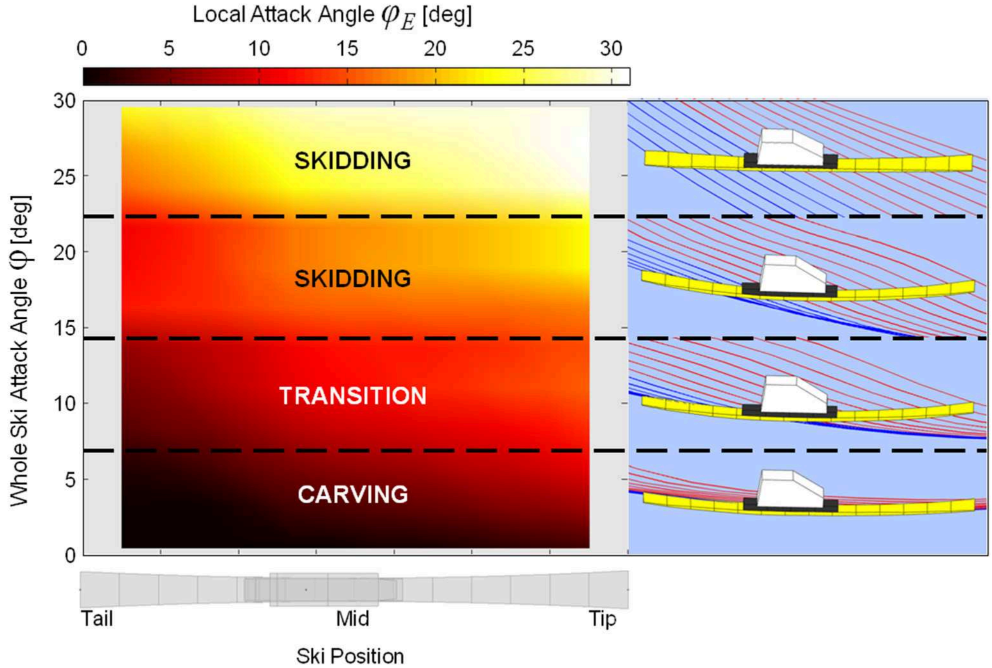

FIGURE 5 | Mean local ski attack angle averaged across whole ski attack angle (left panel). An example ski making the transition from skidding to carving through a turn is shown in the right panels.

the complex interaction of variables influencing the ski-snow interaction. This relatively strong association between Howe's model and measured data seems to indicate how important ski geometric properties—in particular the sidecut radius—are in determining a ski's behavior on snow during carved turns at high edge angles. At low edge angles, however, Howe's equation greatly underestimated the actual turn radius. This contrasts with earlier studies (Federolf, 2005; Federolf et al., 2010a,b) where it was found that Howe's equations performed better at low edge angles and systematically underestimated the actual turn radius at edge angles higher than ∼45 degrees. In the current investigation, it was not until edge angles reached over 70 degrees that R_{HOWE} appeared to underestimate R_{SKI} (on the 13 m course). One possibility for this contrast in results may be that the current investigation was conducted on a relatively hard snow surface where penetration depths were limited such that the ski's deformation more closely matched the shape of the groove being generated in the snow and the ski's trajectory.

There were, nevertheless, two situations in which Howe's Equation 1 failed to capture the ski's trajectory. First, R_{SKI} and R_{HOWE} differed substantially during the transition between turns where R_{SKI} approached infinity and R_{HOWE} approached a limit of R_{SC}, similar to Wimmer's (2001) findings. That the ski can carve at turn radii much longer than that predicted by Equation 1 for low edge angles may be explained to a certain extent by the ski's physical properties. Torsional stiffness plays an important role as the ski shovel and tail twist under the moments generated during their interaction with the snow. If the resulting torsional deformations are large enough to reduce the ski's local edge angle below a certain threshold, that portion of the ski will disengage from the snow and begin to skid or lose contact with the snow entirely. LeMaster (1999) explained that at low edge angles this phenomenon may reduce the engaged, carving section of the ski to the middle portion that has less sidecut, in effect decreasing the ski's turn radius. If this holds true, then the ski's physical properties, including its flexural and torsional stiffness distributions, are important parameters which affect the carving ski's trajectory at low edge angles.

Howe's Equation 1 also did not capture well the large, intermittent fluctuations in R_{SKI} that were apparent, particularly on the 13 m course (**Figure 7**). That these disturbances in ski trajectory did not occur to the same degree on the 10 m course seems counter-intuitive knowing that there was a greater degree of skidding on the 10 m course and suggests that somehow the mechanism may be associated with carving mechanics. This result is perhaps particularly striking considering that other researchers have also observed possibly related phenomena when studying carved turns. Of particular note, Federolf (2005) and Federolf et al. (2010b) observed times where the outside ski reduced turning in the first portion of the turn in his kinematic analysis of carving ski trajectories in giant slalom which they attributed to lateral drifting. In their comparison of an athlete skiing on carving and conventional equipment, Raschner and colleagues (Raschner et al., 2001; Müller and Schwameder, 2003) reported irregular force-time curves when skiing on the carving equipment, an unexpected finding that they also attributed to repeated lateral skidding.

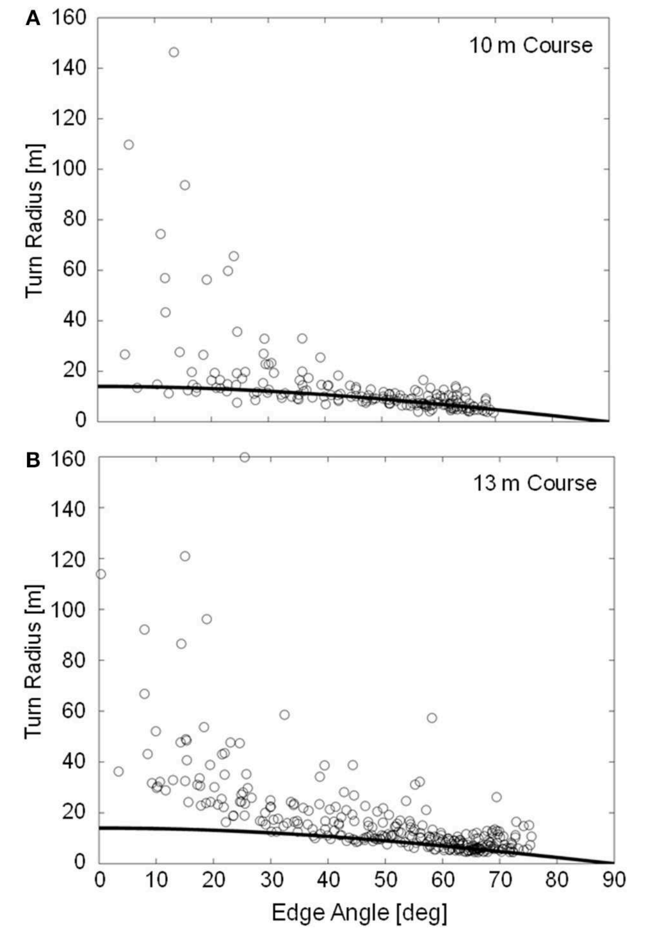

FIGURE 6 | Instantaneous measured outside ski turn radius (R_T, data points) and predicted outside ski turn radius using Equation 1 (R_{HOWE}, data line) for the 12 analyzed trials on the 10 m **(A)** and 13 m **(B)** courses. Data are limited to time points where the ski was carving ($\phi < 5°$, $n = 185$ and 298 for the 10 and 13 m courses, respectively).

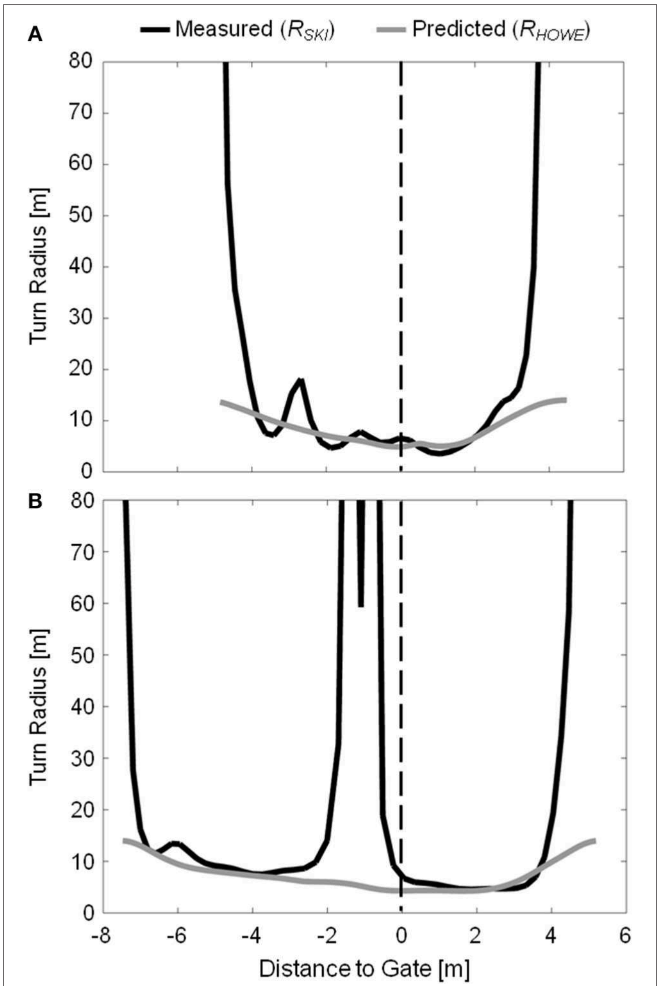

FIGURE 7 | Measured (R_{SKI}, dark lines) and predicted (R_{HOWE}, gray lines) outside ski turn radius for sample turns on the 10 m **(A)** and 13 m **(B)** courses. Due to the different course setting, the data from the two courses are coordinated using the gate as a common point, and presenting the X axis as distance to gate. The vertical dashed line indicates gate passage.

One obvious explanation for these occurrences could simply be that irregularities in the snow surface interfered with the ski's trajectory and resulted in drifting or skidding. This possibility cannot be ruled out in the current investigation. However, there are alternative explanations which we believe are more likely. The fact that these disturbances occurred to a greater extent on the 13 m course suggests that differences in carving and skidding ski-snow interaction mechanics may help explain their occurrence. One such important difference is the process of groove formation. When carving, the ski will be tilted slightly in the snow so that the foremost points on the ski are disengaged from the surface (Lieu and Mote, 1985). The relatively soft tip is then free to vibrate back and forth in flexion and torsion as the shovel digs the groove in which the remainder of the ski will follow. It may be that at times when the tip sways toward the outside of the turn, it catches and engages in the snow surface, consequently redirecting groove formation toward the outside of the turn and away from the skier. There is some observational evidence that this may be the case. An example of this phenomenon is shown in **Figure 8** which shows a photo sequence generated from high-speed video taken during a women's World Cup giant slalom. This mechanism by which the ski may unexpectedly take a trajectory away from the skier could, in the most extreme cases, lead to potentially injurious situations such as the "slip-catch" and "dynamic snowplow" mechanisms described by Bere et al. (2011).

That all of the 12 analyzed turns on the 13 m course showed some form of disturbance just prior to gate passage suggests another, perhaps related mechanism. During the first half of the turn, outside ski trajectories on the 13 m course were much higher on the slope, relative to the approaching gate, than on the 10 m course. Moreover, skis were edged and turning much higher on the slope on the 13 m course (see **Figure 4**) while after gate passage the trajectories from both courses were similar. It may be that on the 13 m course, skis turned too much, too high on the slope relative to the approaching gate, and that the disturbances

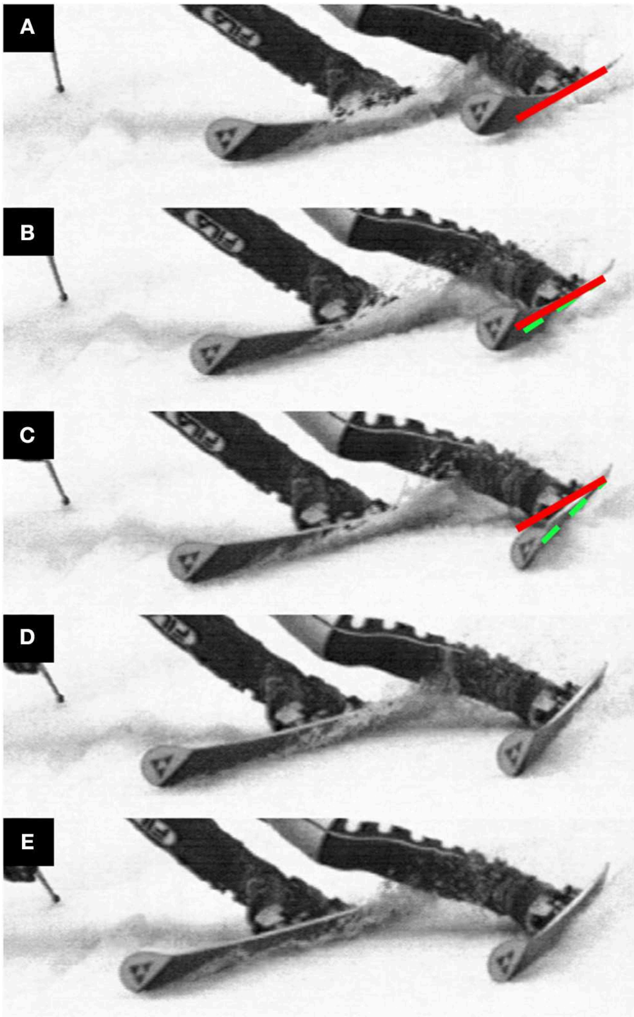

FIGURE 8 | High-speed video footage of a carving ski undergoing a disturbance possibly similar to that observed in the current investigation. This video, taken during the women's World Cup giant slalom at Åre in March, 2006, was filmed at 1,500 fps. To help the reader visualize the outside ski's motion, the solid, black line indicates the original ski orientation from Frame **(A)** while the dashed, white line indicates the changing ski's orientation. From Frame **(A–C)**, the ski shovel sways toward the outside of the turn. The shovel reaches and engages the snow surface in Frame **(C)**. Groove formation is then redirected onto a new trajectory in Frames **(D, E)** with the increased distance between the skier's feet indicating that the outside and inside skis have come onto diverging trajectories.

measured in ski turn radius were actually the result of having to reorient the ski onto a new trajectory to avoid skiing on the wrong side of the gate.

That the ski seems to be re-oriented suddenly, as opposed to gradually corrected over the entire first half of the turn, may indicate that the skier's control over the degree to which a carving ski turns for a given edge angle is more limited than traditionally thought. Taking this line of reasoning further, an explanation for why these disturbances did not occur on the 10 m course to the same extent as on the 13 m course may be that the ski's trajectory on the 10 m course more closely matched its physical and geometrical characteristics so that the skiers did not have to correct its trajectory during the turn.

CONCLUSIONS AND FURTHER PERSPECTIVES

In summary, this study has captured ski motion characteristics during slalom race simulations and compared these measures with theoretical predictions of ski motion. During the transition from skidding, the tail of the ski initiated carving as the ski attack angle reduced below 8 degrees, in good accordance with Lieu and Mote's results (Lieu, 1982; Lieu and Mote, 1985). The ski reached an advanced carving stage at whole ski attack angles of ∼3 degrees, although local attack angles along the ski forebody remained slightly elevated, also in good accordance with theoretical models of ski shovel function during carving (Lieu, 1982; Lieu and Mote, 1985; Yoneyama et al., 2008; Tatsuno et al., 2009; Federolf et al., 2010b).

Important insight into ski function can be gained by studying how measured ski trajectories compare to prediction models that are based on the shape of the deformed ski, such as Howe's models (Howe, 2001). In this investigation, Howe's equation (Equation 1) performed surprisingly well for edge angles above ∼45 degrees indicating that ski geometry, in particular sidecut radius, is an important variable determining the ski's trajectory at high edge angles. On a practical level, these results suggest that the skier's trajectory will largely be determined by the ski sidecut radius in a carved turn at high edge angles. This understanding may have consequences for equipment design and course setting both with respect to performance and safety (Kröll et al., 2016a,b).

The results from this study were more complicated for lower edge angles, however. Howe's Equation 1 prediction accuracy progressively degraded with decreasing edge angles, which is in good agreement with some previous work (Wimmer, 2001) but in contrast with others (Federolf et al., 2010a). This suggests that variables other than sidecut radius alone influence the ski's trajectory at low edge angles, such as other ski physical properties or skier technique. Therefore, future investigations should consider how ski geometry, in combination with flexural and torsional stiffness distributions, determine the carving ski's trajectory on different types of snow conditions. This study has focused on carved turns. However, understanding how equipment characteristics influence skidded turns is equally important. Following this line of research to better understand how ski characteristics influence the ski-snow interaction can support the ski industry in developing equipment for improved performance, enjoyment and safety.

DATA AVAILABILITY STATEMENT

The datasets for this article are not publicly available due to intellectual property reasons. Requests to access the datasets should be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ombudsman for Privacy in Research, Norwegian Social Science Data Services, AS. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

RR, PH, MG, and RK conducted the data collection. RR, MG, and GS conducted the analysis. All authors contributed to the writing, publication of the study, and design and scientific content of the study.

FUNDING

The study was funded by the Norwegian School of Sport Sciences, the Norwegian Olympic and Paralympic Committee and Confederation of Sports and the Norwegian Ski Federation.

ACKNOWLEDGMENTS

The authors thank master students Tron Moger and Håvard Tjørhom for their valuable contribution to the study.

REFERENCES

Bere, T., Florenes, T. W., Krosshaug, T., Koga, H., Nordsletten, L., Irving, C., et al. (2011). Mechanisms of anterior cruciate ligament injury in World Cup alpine skiing: a systematic video analysis of 20 cases. *Am. J. Sports Med.* 39, 1421–1429. doi: 10.1177/0363546511405147

Brown, C., and Outwater, J. O. (1989). "On the skiability of snow," in *Skiing Trauma and Safety: Seventh International Symposium, ASTM STP 1022*, eds. R. J. Johnson, C. D. Mote, and M. Binet (Philadelphia: American Society for Testing and Materials), 329–336. doi: 10.1520/STP19480S

Casolo, F., and Lorenzi, V. (2001). "Relevance of ski mechanical and geometrical properties in carving technique: A dynamic simulation," in *Science and Skiing II*, eds E. Müller, H. Schwameder, C. Raschner, S. Lindinger, and E. Kornexl (Hamburg: E & FN Spon), 165–179.

Challis, J. H. (1999). A procedure for the automatic determination of filter cutoff frequency for the processing of biomechanical data. *J. Appl. Biomech.* 15:317. doi: 10.1123/jab.15.3.303

Federolf, P. (2005). *Finite Element Simulation of a Carving Snow Ski*. Zurich: ETH Zurich.

Federolf, P., Lüthi, A., Roos, M., and Dual, J. (2010a). Parameter study using a finite element simulation of a carving Alpine ski to investigate the turn radius and its dependence on edging angle, load, and snow properties. *Sport. Eng.* doi: 10.1007/s12283-010-0039-y

Federolf, P., Reid, R., Gilgien, M., Haugen, P., and Smith, G. (2012). The application of principal component analysis to quantify technique in sports. *Scand. J. Med. Sci. Sports* 24, 491–499. doi: 10.1111/j.1600-0838.2012.01455.x

Federolf, P., Roos, M., Lüthi, A., and Dual, J. (2010b). Finite element simulation of the ski snow interaction of an alpine ski in a carved turn. *Sport. Eng.* 12, 123–133. doi: 10.1007/s12283-010-0038-z

Florenes, T. W., Bere, T., Nordsletten, L., Heir, S., and Bahr, R. (2009). Injuries among male and female World Cup alpine skiers. *Br. J. Sports Med.* 43, 973–978. doi: 10.1136/bjsm.2009.068759

Florenes, T. W., Nordsletten, L., Heir, S., and Bahr, R. (2012). Injuries among World Cup ski and snowboard athletes. *Scand. J. Med. Sci. Sports* 22, 58–66. doi: 10.1111/j.1600-0838.2010.01147.x

Gilgien, M., Crivelli, P., Spörri, J., Kröll, J., and Müller, E. (2015a). Characterization of course and terrain and their effect on skier speed in World Cup alpine ski racing. *PLoS ONE* 10:e0118119. doi: 10.1371/journal.pone.0118119

Gilgien, M., Crivelli, P., Spörri, J., Kröll, J., and Müller, E. (2015b). Correction: Characterization of course and terrain and their effect on skier speed in World Cup alpine ski racing. *PLoS ONE* 10:e0118119.

Gilgien, M., Kröll, J., Spörri, J., Crivelli, P., and Müller, E. (2018). Application of dGNSS in alpine ski racing: Basis for evaluating physical demands and safety. *Front. Physiol.* 9:145. doi: 10.3389/fphys.2018.00145

Gilgien, M., Spörri, J., Chardonnens, J., Kröll, J., Limpach, P., and Müller, E. (2015c). Determination of the centre of mass kinematics in alpine skiing using differential global navigation satellite systems. *J. Sports Sci.* 33, 960–969. doi: 10.1080/02640414.2014.977934

Gilgien, M., Spörri, J., Chardonnens, J., Kröll, J., and Müller, E. (2013). Determination of external forces in alpine skiing using a differential global navigation satellite system. *Sensors* 13, 9821–9835. doi: 10.3390/s130809821

Gilgien, M., Spörri, J., Kröll, J., and Müller, E. (2016). Effect of ski geometry and standing height on kinetic energy: equipment designed to reduce risk of severe traumatic injuries in alpine downhill ski racing. *Br. J. Sports Med.* 50, 8–13. doi: 10.1136/bjsports-2015-095465

Haaland, B., Steenstrup, S. E., Bere, T., Bahr, R., and Nordsletten, L. (2015). Injury rate and injury patterns in FIS World Cup alpine skiing (2006-2015): have the new ski regulations made an impact? *Br. J. Sports Med.* doi: 10.1136/bjsports-2015-095467

Heinrich, D., Mossner, M., Kaps, P., and Nachbauer, W. (2010). Calculation of the contact pressure between ski and snow during a carved turn in alpine skiing. *Scand. J. Med. Sci. Sports* 20, 485–492. doi: 10.1111/j.1600-0838.2009.00956.x

Heinririch, D., Mössner, M., Kaps, P., Schretter, H., and Nachbauer, W. (2006). "Influence of ski bending stiffness on the turning radius of alpine skis at different edging angles and velocities," in *The Engineering of Sport 6,* eds E. F. Moritz, and S. Haake (New York, NY: Springer), 207–212. doi: 10.1007/978-0-387-46051-2_37

Hirano, Y. (2006). Quickest descent line during alpine ski racing. *Sport. Eng.* 9, 221–228. doi: 10.1007/BF02866060

Hirano, Y., and Tada, N. (1996). Numerical simulation of a turning alpine ski during recreational skiing. *Med. Sci. Sports Exerc.* 28, 1209–1213. doi: 10.1097/00005768-199609000-00020

Howe, H. (2001). *The New Skiing Mechanics*. Vancouver, BC: McIntire Publishing.

Joubert, G. (1980). *Skiing. An art. A technique*. LaPorte, CO: Poudre Publishing Company.

Kagawa, H., Yoneyama, T., Tatsuno, D., Scott, N., and Osada, K. (2009). "Development of a measuring system on ski deflction and contacting snow pressure in turns," in *Science and Skiing IV*, eds. E. Müller, S. Lindinger, and T. Stöggl (Maidenhead: Meyer & Meyer Sport, Ltd.), 281–291.

Kaps, P., Mossner, M., Nachbauer, W., and Stenberg, R. (2001). "Pressure distribution under a ski during carved turns," in *Science and Skiing*, eds. E. Müller, H. Schwameder, C. Raschner, S. Lindinger, and E. Kornexl (Hamburg: E & FN Spon), 180–202.

Kröll, J., Spörri, J., Gilgien, M., Schwameder, H., and Müller, E. (2016a). Effect of ski geometry on aggressive ski behaviour and visual aesthetics: equipment designed to reduce risk of severe traumatic knee injuries in alpine giant slalom ski racing. *Br. J. Sports Med.* 50, 20–25. doi: 10.1136/bjsports-2015-095433

Kröll, J., Spörri, J., Gilgien, M., Schwameder, H., and Müller, E. (2016b). Sidecut radius and the mechanics of turning: equipment designed to reduce risk of severe traumatic knee injuries in alpine giant slalom ski racing. *Br. J. Sports Med.* 50, 14–19. doi: 10.1136/bjsports-2015-095737

LeMaster, R. (1999). *The skiers Edge*. Champaign, IL: Human Kinetics.

Lieu, D. K. (1982). *Mechanics of the Turning Snow-Ski*. Berkeley, CA: University of California.

Lieu, D. K., and Mote, C. D. (1985). "Mechanics of the turning snow ski," in *Skiing Trauma and Safety: Fifth International Symposium*, eds. R. J. Johnson, and C. D. Mote (Philadelphia: American Society for Testing and Materials), 117–140. doi: 10.1520/STP46631S

Lind, D., and Sanders, S. (2004). *The Physics of Skiing: Skiing at the Triple Point*, 2nd Edn. New York, NY: Springer. doi: 10.1007/978-1-4757-4345-6

Mossner, M., Heinrich, D., Kaps, P., Schretter, H., and Nachbauer, W. (2010). Computer simulation of consecutive ski turns. *J. ASTM Int.* 5, 126–136. doi: 10.1520/JAI101387

Mössner, M., Heinrich, D., Schindelwig, K., Kaps, P., Lugner, P., Schmiedmayer, H., et al. (2006). "Modeling of the ski-snow contact for a carved turn," in *The engineering of sport 6*, eds. E. Moritz, and S. Haake (New York, NY: Springer), 195–200. doi: 10.1007/978-0-387-46051-2_35

Müller, E., Bartlett, R., Raschner, C., Schwameder, H., Benko-Bernwick, U., and Lindinger, S. (1998). Comparisons of the ski turn techniques of experienced and intermediate skiers. *J. Sports Sci.* 16, 545–559. doi: 10.1080/026404198366515

Müller, E., and Schwameder, H. (2003). Biomechanical aspects of new techniques in alpine skiing and ski-jumping. *J. Sports Sci.* 21, 679–692. doi: 10.1080/0264041031000140284

Pourcelot, P., Audigie, F., Degueurce, C., Geiger, D., and Denoix, J. M. (2000). A method to synchronize cameras using the direct linear transformation technique. *J. Biomech.* 33, 1751–1754. doi: 10.1016/S0021-9290(00)00132-9

Raschner, C., Schiefermüller, C., Zallinger, G., Hofer, E., Müller, E., and Brunner, F. (2001). "Carving turns versus traditional parallel turns - a comparative biomechanical analysis," in *Science and Skiing*, eds. E. Müller, H. Schwameder, C. Raschner, S. Lindinger, and E. Kornexl (Hamburg: E & FN Spon), 203–217.

Reid, R., Gilgien, M., Moger, T., Tjørhom, H., Haugen, P., Kipp, R., et al. (2009). "Turn characteristics and energy dissipation in slalom," in *4th International Congress on Science and Skiing*, eds. E. Müller, S. Lindinger, and T. Stögg (Maidenhead: Meyer & Meyer Sport, Ltd.), 419–427.

Reid, R. C. (2010). *A kinematic and kinetic Study of Alpine Skiing Technique in Slalom*. Available online at: https://brage.bibsys.no/xmlui/bitstream/handle/11250/171325/reidphd~2010.pdf?sequence=1&isAllowed=y (accessed December 10, 2019).

Renshaw, A. A., and Mote, C. D. (1989). A model for the turning snow ski. *Int. J. Mech. Sci.* doi: 10.1016/0020-7403(89)90040-4

Sahashi, T., and Ichino, S. (1998). Coefficient of kinetic friction of snow skis during turning descents. *Jap. J. Appl. Phys.* 37, 720–726. doi: 10.1143/JJAP.37.720

Spörri, J., Kröll, J., Gilgien, M., and Müller, E. (2016a). How to prevent injuries in alpine ski racing: what do we know and where do we go from here? *Sport. Med.* 47, 1–16. doi: 10.1007/s40279-016-0601-2

Spörri, J., Kröll, J., Gilgien, M., and Müller, E. (2016b). Sidecut radius and the mechanics of turning-equipment designed to reduce risk of severe traumatic knee injuries in alpine giant slalom ski racing. *Br. J. Sports Med.* 50, 14–19.

Tada, N., and Hirano, Y. (2002). "In search of the mechanics of a turning alpine ski using snow cutting force measurements," in *Sports Engineering 5* (Berlin: Blackwell Science Ltd.), 15–22. doi: 10.1046/j.1460-2687.2002.00092.x

Tatsuno, D., Yoneyama, T., Kagawa, H., Scott, N., and Osada, K. (2009). "Measurement of ski deflection and ski-snow contacting pressure in an actual ski turn on the snow surface.," in *Science and Skiing IV*, eds. E. Müller, S. Lindinger, and T. Stögg (Maidenhead: Meyer & Meyer Sport, Ltd.), 505–515.

Wimmer, M. A. (2001). *Kinetische und kinematische analyse von Schwüngen im alpinen skilauf*. Master thesis, Leopold-Franzens-Universität Innsbruck, Innsbruck, Austria.

Yoneyama, T., Scott, N., Kagawa, H., and Osada, K. (2008). Ski deflection measurement during skiing and estimation of ski direction and edge angle. *Sport. Eng* 11, 3–13. doi: 10.1007/s12283-008-0001-4

Zorko, M., Nemec, B., Babic, J., Lesnik, B., and Supej, M. (2015). The waist width of skis influences the kinematics of the knee joint in Alpine skiing. *J Sport. Sci Med.* 14, 606–619.

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.

frontiers in Sports and Active Living

ORIGINAL RESEARCH
published: 28 April 2020
doi: 10.3389/fspor.2020.00044

Effect of Sitting Posture on Sit-Skiing Economy in Non-disabled Athletes

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OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Sports Science, Technology and Engineering, a section of the journal Frontiers in Sports and Active Living

Received: 05 September 2019
Accepted: 31 March 2020
Published: 28 April 2020

Citation:
Lajunen K, Rapp W, Ahtiainen JP, Lindinger SJ and Linnamo V (2020) Effect of Sitting Posture on Sit-Skiing Economy in Non-disabled Athletes. Front. Sports Act. Living 2:44. doi: 10.3389/fspor.2020.00044

This study focused on resolving the differences in economy between two common sit-skiing postures used by disabled athletes, suspected to be the most and least effective. Ten experienced non-disabled male cross-country skiers went through an incremental testing protocol with an ergometer simulating double poling in two sitting postures "kneeing" and "knee-high." The protocol consisted of 3 × 4 min steady-state stages (13, 22, and 34% of maximal sprint power output). Subjects' respiratory gases and heart rate were measured and blood lactate concentrations were determined. In addition, pulling forces and motion capture recordings were collected. Oxygen consumption was 15.5% ($p < 0.01$) higher with "knee-high" compared to "kneeing" at stage three. At stage three cycle rate was 13.8% higher ($p < 0.01$) and impulse of force 13.0% ($p < 0.05$) and hip range of motion 46.6% lower ($p < 0.01$) with "knee-high" compared to "kneeing." "Kneeing" was found to be considerably more economical than "knee-high" especially at 34% of maximum sprint power output. This might have been due to higher cycle rate, lower impulse of force and smaller hip range of motion with "knee-high" compared to "kneeing." This indicates that sit-skiers should adopt, if possible, posture more resembling the "kneeing" than the "knee-high" posture. Combining such physiological and biomechanical measurements and to further develop them to integrated miniature wearable sensors could offer new possibilities for training and testing both in the laboratory and in the field conditions.

Keywords: paralympics, classification, competition, oxygen consumption, trunk movement

INTRODUCTION

Cross-country skiing is one of the six sports in the winter Paralympic Games (International Paralympic Committee, 2020d) and sit-skiers form one of the three major sport classes in cross-country skiing (International Paralympic Committee, 2020b). In a sit-skiing event, each athlete sits on a sledge mounted on top of a pair of traditional cross-country skis and creates forward propulsion using the double poling (DP) technique (Gastaldi et al., 2012). DP in general refers to a skiing technique in which both poles are planted to the ground simultaneously and trunk flexion is synchronized with shoulder and elbow extension to create propulsive force (Smith et al., 1996). Due to the important role of the legs in DP of able-bodied skiers (Holmberg et al., 2005, 2006), the DP of sit-skiers is obviously different. For example, sit-skiers begin the poling phase with their hands above the level of their head (Gastaldi et al., 2012; Bernardi et al., 2013). Able-bodied skiers can utilize their full body mass to produce impulse to the poles (Holmberg et al., 2005), while disabled skiers are not able to do so.

To make sure that athletes can compete equitably with each other in sit-skiing they are classified based on their physical impairment and functional capability (International Paralympic Committee, 2020c). Locomotor Winter (LW) is a para-Alpine and para-Nordic sit-skiing classification defined by the International Paralympic Committee. Sit-skiers are allocated to five different classes: LW10, LW10.5, LW11, LW11.5, LW12. Class LW10 athletes have impairment affecting both their trunk and lower limbs. These athletes, while properly strapped over the legs to the test table, are unable to maintain a sitting position with their abdominal muscles or trunk extensors working against gravity without arm support. Class LW12 athletes' impairments are limited to their lower limbs (International Paralympic Committee, 2020c). Classes LW10–12 compete in the same category and a specific percentage-system is utilized to make competition equitable, which means that the competitor's actual finishing time is multiplied by the specific percentage to calculate their adjusted finishing time (International Paralympic Committee, 2020b). The current percentages for LW10–LW12 classes are 86, 90, 94, 97, and 100%, respectively (International Paralympic Committee, 2020a). These percentages have been determined based on the World Cup competition results from previous years.

In Paralympic sit-skiing, two common sitting postures are observable primarily based on the level of impairment of the athletes. The rules do not designate athletes in a certain class to use a certain posture but the athletes try to obtain the position that would be most optimal with them. To achieve a stable sitting posture, athletes with high impairment (LW10 and LW10.5) use a posture where the knees are higher than the pelvis ("knee-high") (see **Figure 1**). The other posture, "kneeing," enables a more extensive hip range of motion (ROM) compared to the "knee-high" posture and is preferred by athletes with full trunk function. Gastaldi et al. (2012) showed that a skier using the "kneeing" posture has considerably more extensive trunk movement compared to a skier sitting in the "knee-high" posture. This is supported by our recent findings with able-bodied athletes that not only is the hip ROM smaller but also less power and lower maximal velocity can be obtained with the "knee-high" posture as compared to the "kneeing" posture (Rapp et al., 2013).

The importance of skiing economy for performance has been demonstrated in several studies in able-bodied athletes (Mahood et al., 2001; Mikkola et al., 2010; Ainegren et al., 2013). Mahood et al. (2001) observed a strong correlation between skiing performance and skiing economy. More recently, Ainegren et al. (2013) demonstrated that elite cross-country skiers had better skiing economy than recreational skiers and senior elite skiers were more economical compared to elite juniors. It has also been noted that there is a negative relationships between the velocity in a simulated sprint competition and oxygen consumption and blood lactate concentration in a 2 km constant velocity DP test (Mikkola et al., 2010).

Paralympic athletes differ based on their impairment level, functional capacity, and technique (International Paralympic Committee, 2020c). The classification process, however, may not take into account the additional disadvantage that some skiers face due to their sitting postures. To ensure that sit-skiers with various levels of impairments and different sitting postures can compete equally, it is essential to understand how sitting posture affects sit-skiing economy. In order to solely determine the difference in economy between different postures one posture should not be more favorable for some subjects than for the others. Disabled skiers have a wide variability in level of impairment and they become accustomed to one posture during their training. These issues could affect scientific evaluation of the two postures. Therefore, the aim of this study was to examine the differences in respiratory gases, blood lactate, force production and joint kinematics in non-disabled athletes between two common sit-skiing postures ("kneeing" and "knee-high") observable in Paralympic sit-skiing competitions. This information could help coaches improve sitting postures for their athletes and possibly provide more scientific knowledge from which to base the classification system. It was hypothesized that due to larger trunk range of motion the "kneeing" position would be more effective and economical than "knee-high" position.

METHODS

Experimental Approach to the Problem

An experimental study was designed to examine the effect of sitting posture on sit-skiing economy and associated biomechanical factors. The testing protocol consisted of 3 × 4 min incremental stages with both postures on a ski ergometer (Concept2, Morrisville, Vermont, USA) simulating DP. The resistance of the ergometer was set at six (scale 1–10) throughout the present study. To eliminate the effect of order, each stage was performed in both postures in a randomized fashion before proceeding to the next stage and the starting posture was randomized. Recovery periods between the stages were 2 min. Before the incremental protocol subjects warmed up for 5 min during which they carried out two short (5–10 s), near maximal sprints. After warm-up, subjects completed one maximal sprint (10–15 s) in the "kneeing" position in which the athletes were expected to achieve the highest maximal power output, which was then recorded. In order to compare the same absolute working loads powers outputs corresponding to 13, 22, and 34% of this maximum value were the stages used in the incremental protocol with "kneeing" and "knee-high" sitting positions. These two extreme positions were chosen based on our previous study where we examined four different sitting positions and observed the greatest differences in maximal velocity in these two positions (Rapp et al., 2013). During the stages, subjects were instructed to maintain the correct power output as accurately as possible. The current power output was displayed in real-time on the ergometer, which the authors carefully monitored and gave verbal feedback when necessary to maintain the target intensity.

Subjects

Ten healthy male cross-country skiers (Age 22 ± 5 yrs., height 177 ± 6 cm, weight 71 ± 5 kg, reported VO_2max 73 ± 5 ml•min^{-1}•kg^{-1}) volunteered to participate in the study. All participants had competed in cross-country skiing at the Finnish national level for at least 5 years. Before the start of the study,

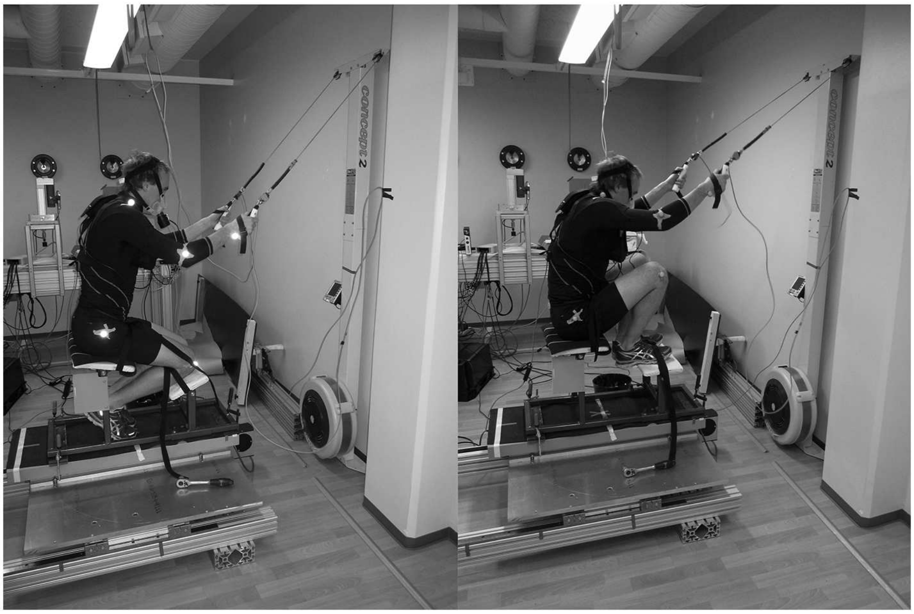

FIGURE 1 | Illustration of the experimental setup during the **(A)** "kneeing" posture and **(B)** "knee-high" posture.

athletes were informed about the design of the study, with a special emphasis on possible risks and benefits, and they signed an informed consent document. In the case of one subject who was under 18 years old at the time of the study, parental consent was received. The study was performed according to the Declaration of Helsinki, and the Ethical Committee of the University of Jyväskylä approved the study.

Procedures

A portable telemetry-based ergospirometer Cortex MetaMax 3B (Cortex Biophysik, Leipzig, Germany) was used for all respiratory gas measurements. This apparatus was connected (wirelessly) to MetaSoft 3.2 software on a computer. The variables of interest were oxygen consumption (VO_2) relative to body weight, ventilation (VE) and respiratory exchange ratio (RER). Heart rate (HR) was measured using Polar Wearlink (Polar Electro Oy, Kempele, Finland) heart rate belt, which was also wirelessly connected to MetaSoft 3.2 software. Heart rate and respiratory variables were determined as average steady-state values during the last minute of each stage. Blood samples from the fingertip were taken within the first minute after each stage. From these samples blood lactate concentrations were determined using Lactate Pro (Carlton, Australia) portable blood lactate analyzer.

Pulling forces were measured using force –sensors (University of Jyväskylä, Finland), which were placed between the ergometer's handles and their strings. For kinematic analysis, six infrared cameras (Vicon Motion Systems Ltd., Oxford, UK) were used. In order to perform these recordings, small reflective markers were attached to the standardized positions in the subjects' knee, hip, shoulder, elbow, and wrist on the right side of the body. Illustrative examples of the experimental setup and the two sitting postures are shown in **Figures 1A,B**. Recordings of these biomechanical measurements were done synchronously during the second to last 30-s period of each stage using Vicon Nexus 1.8.3 software (Vicon Motion Systems Ltd., Oxford, UK). This software was also used to prepare the biomechanical data, which was ultimately analyzed with Ike Master 1.38 software (IKE Software Solutions, Salzburg, Austria). Biomechanical variables of interest were cycle rate, relative poling time, impulse of poling force and range of motion (ROM) of elbow, shoulder and hip joints. ROMs were analyzed in three dimensional space during poling phase (from the beginning till the end of the force production) as follows: Elbow ROM as a change in angle formed by lines between shoulder and elbow markers and elbow and wrist markers, shoulder ROM as a change in angle formed by lines between shoulder and elbow markers and shoulder and hip markers, and finally hip ROM as a change in angle formed by lines between shoulder and hip markers and hip and knee markers. All the biomechanical variables were analyzed as an average of nine consecutive cycles from the right side of the body.

Statistical Analyses

The data was analyzed using SPSS software version 16.0 (SPSS Inc., Chicago, IL, USA). The results are expressed as mean ± SD. Sixty three of the total 66 variables were normally distributed and the normal Gaussian distribution of the data was verified by the Shapiro - Wilks test. A two-way, Posture (Bernardi et al., 2013) × Stage (Gastaldi et al., 2012), repeated measures ANOVA was performed to analyze the differences in the physiological and biomechanical variables between the two postures during the three stages. Furthermore, paired samples T-tests were run between the two postures on every stage

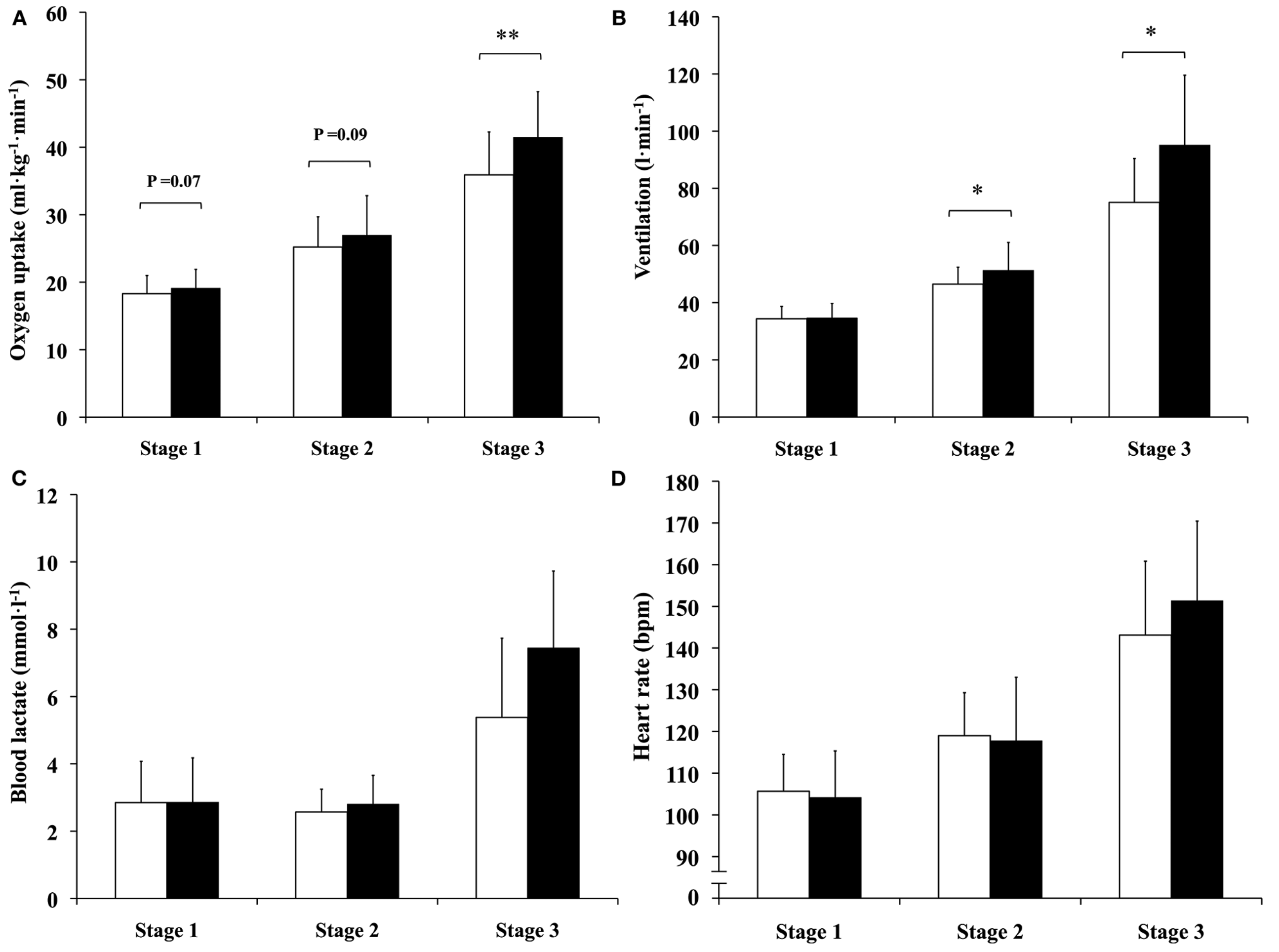

FIGURE 2 | Differences in: **(A)** oxygen uptake, **(B)** ventilation, **(C)** blood lactate concentration, and **(D)** heart rate between "kneeing" (white columns) and "knee-high" (black columns) postures during stages one, two and three (13, 22 and 34 percent of maximum sprint power output, respectively). *Statistically significant difference between "kneeing" and "knee-high" postures (* $p < 0.05$, ** $p < 0.01$).

and the Holm-Bonferroni method applied for the yielded *p*-values by multiplying all pairwise p-values with the number of comparisons conducted for each variable. The following variables were not normally distributed: VO_2 at stage one in "knee-high" posture, blood lactate concentration at stage one in "kneeing" posture, and shoulder ROM at stage one in "kneeing" posture. Statistical differences between these three variables and their corresponding pairs were determined using non-parametric functions. Spearman's rank correlations were calculated between relative differences in oxygen consumption differences and relative differences in the biomechanical variables. In all statistical tests, differences were significant when $P < 0.05$.

RESULTS

Power Outputs

The mean value for the power output in the maximum sprint was 292 ± 51 W. The power outputs for stages one, two, and three were 37 ± 6 W, 63 ± 11 W and 100 ± 18 W, corresponding to 13, 22, and 34%, of maximal power output, respectively.

Differences in Physiological Variables

Oxygen consumption ($P < 0.01$), ventilation ($P < 0.05$) and blood lactate concentration ($P < 0.01$) indicated significant differences between the two postures. Oxygen consumption was 15.5% ($P < 0.01$) higher with "knee-high" compared to "kneeing" posture at stage three (**Figure 2A**). Ventilation was 10.2 and 26.7% (both $P < 0.05$) higher with "knee-high" compared to "kneeing" posture at stages two and three, respectively (**Figure 2B**). No significant differences were observed in blood lactate concentration at any stage, despite a significant overall difference observed in ANOVA (**Figure 2C**). Heart rate (**Figure 2D**) and respiratory exchange ratio did not differ statistically during any load.

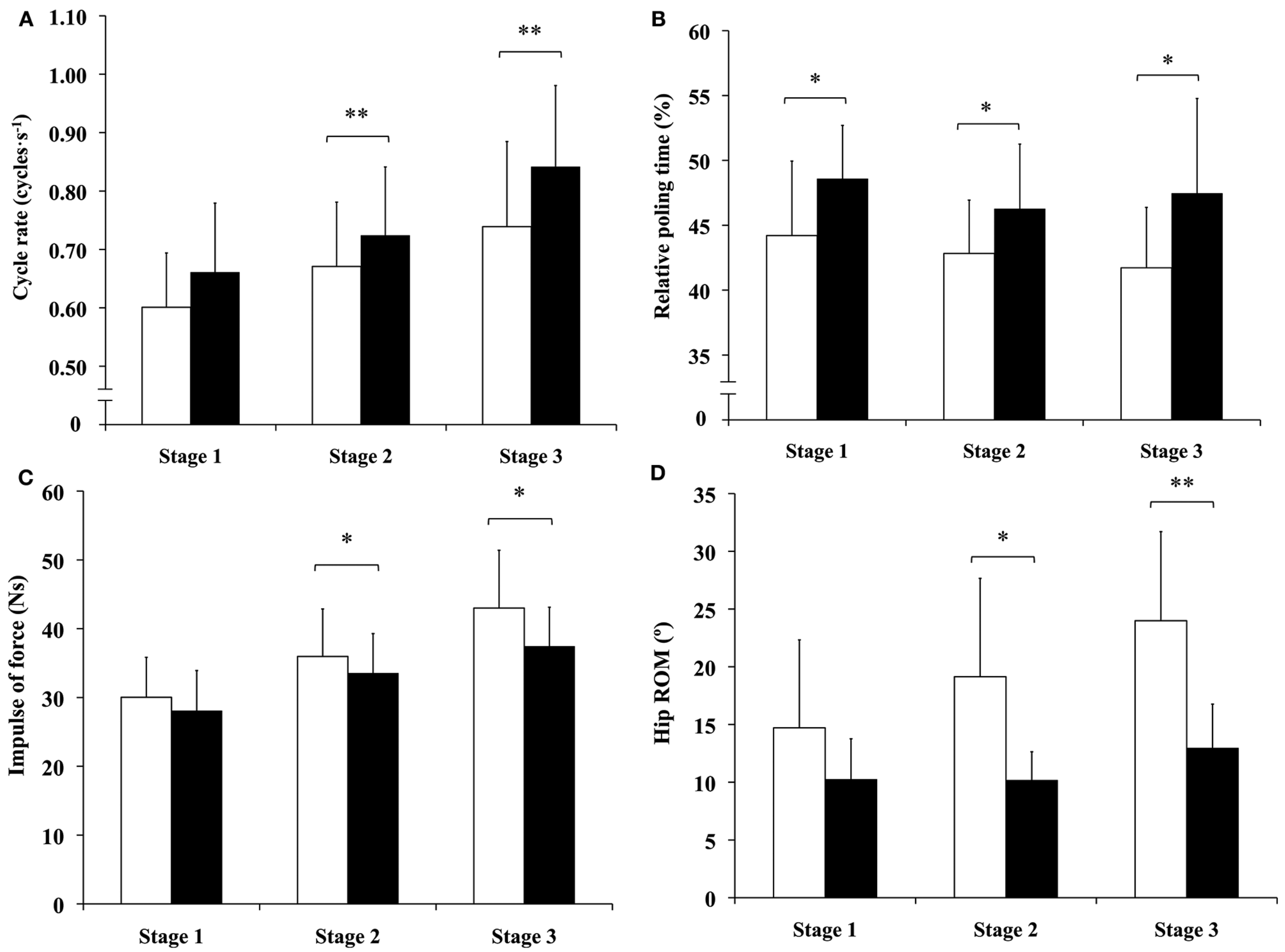

FIGURE 3 | Differences in: **(A)** cycle rate, **(B)** relative poling time, **(C)** impulse of force, and **(D)** hip range of motion between "kneeing" (white columns) and "knee-high" (black columns) postures during stages one, two and three (13, 22, and 34 percent of maximum sprint power output, respectively). *Statistically significant difference between "kneeing" and "knee-high" postures (* $p < 0.05$, ** $p < 0.01$).

Differences in Biomechanical Variables

Cycle rate, relative poling time, impulse of poling force and hip ROM demonstrated significant differences between the two postures (all $P < 0.01$). Cycle rate was 7.9 and 13.8% (both $P < 0.01$) higher with "knee-high" compared to "kneeing" posture at stages two and three, respectively (**Figure 3A**). Relative poling time was 9.9, 8.0, and 13.7% (all $P < 0.05$) higher with "knee-high" compared to "kneeing" posture at stages one, two and three, respectively (**Figure 3B**). Impulse of force was 6.8 and 13.0% (both $P < 0.05$) lower "knee-high" compared to "kneeing" posture at stages two and three, respectively (**Figure 3C**). Hip ROM was 46.8% ($P < 0.05$) and 46.6% ($P < 0.01$) smaller with "knee-high" compared to "kneeing" posture at stages two and three, respectively (**Figure 3D**).

Correlations Between Differences in Economy and Biomechanical Variables

Statistically significant correlations between posture-dependent differences in oxygen consumption and biomechanical variables were observed during stage three. Differences in cycle rate correlated positively to differences in oxygen consumption ($r = 0.648$, $P = 0.043$, $r^2 = 0.42$) (**Figure 4**). In addition, differences in impulse of force ($r = -0.636$, $P = 0.048$, $r^2 = 0.40$) and hip ROM ($r = -0.667$, $P = 0.050$, $r^2 = 0.44$) correlated negatively to differences in oxygen consumption.

DISCUSSION

The main finding of present study was that oxygen consumption was 4.4–15.5% higher with the "knee-high" posture compared to the "kneeing" posture at matched power outputs. Hence, economy was better with the "kneeing" posture. Several other physiological variables supported this finding and posture-dependent differences were observed in a number of biomechanical variables. These findings confirm the results of Gastaldi et al. (2012) who also found that in Paralympic athletes the "kneeing" posture allows for a higher mechanical performance in Paralympic athletes.

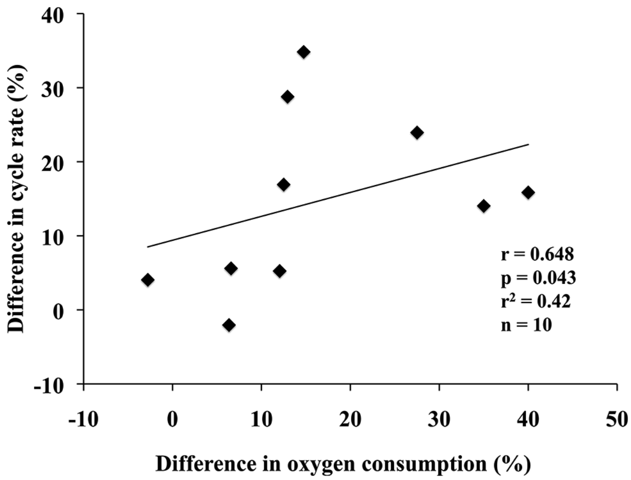

FIGURE 4 | Positive correlation between relative differences of “kneeing” and “knee-high” postures in oxygen consumption and cycle rate during stage three (34 percent of maximum sprint power output).

The “kneeing” posture was found to be more economical compared to the “knee-high” posture. Most importantly, oxygen consumption at the same power output was higher with the “knee-high” posture. In addition, blood lactate concentration and ventilation were significantly higher with the “knee-high” posture. All of these inter-posture differences together provide strong evidence that the “kneeing” posture is more economical than the “knee-high” posture. This was expected based on our previous findings with able-bodied cross-country skiers (Rapp et al., 2013) in which the “kneeing” posture was shown to be considerably more effective than the “knee-high” posture.

In the present study, a number of biomechanical variables were measured to explain the differences in economy between postures. A higher cycle rate and lower impulse of force with the “knee-high” posture indicated that subjects compensated for a lower single cycle impulse by increasing poling frequency. Since relative poling time was also higher with the “knee-high” posture, it seems that subjects needed to shorten the recovery phase of the cycle to maintain the correct velocity. Our finding is in line with a previous study by Gastaldi et al. (2012) who reported that Paralympic athletes had considerably limited hip ROM with the “knee-high” posture. LW12 athletes, who most often use the “kneeing” position, have been shown to have greater trunk range of motion (ROM) compared to the lower classes both when skiing on snow (Gastaldi et al., 2012; Schillinger et al., 2016) and with an ergometer (Rosso et al., 2016). In the “knee-high” sit-skiing posture, trunk flexors cannot be activated extensively and they may operate at less effective muscle lengths compared to the “kneeing” posture. This could explain, at least in part, why the “knee-high” posture led to a higher cycle rate and lower impulse of force in the present study.

During stage three, the relative differences in cycle rate, impulse of force and hip ROM correlated significantly to the relative differences in VO_2. The correlation between relative differences in cycle rate and relative differences in VO_2 was positive. Correlations between relative differences in impulse of force and hip ROM and relative differences in VO_2 were instead negative. These results suggest that a higher cycle rate, lower impulse of force and limited hip ROM with “knee-high” compared to “kneeing” posture are the most probable factors behind the higher VO_2 with “knee-high” posture, although the significance levels and coefficients of determination of each factor individually were relatively low.

There were some limitations in this study. Two-minute rest periods between the stages may not have been sufficient to obtain full recovery even in our high-level athletes. However, by randomizing the order of the postures, any residual fatigue should have little influence on the study’s main findings. The unfamiliarity of the sit-skiing movement may have caused technical difficulties for some subjects, especially during the maximal sprint. It seems unlikely though that these technical problems would have been more emphasized in one of the positions than in the other and thus the main purpose, which was to examine the effect of sitting position to performance, is probably not compromised. Nevertheless, although all efforts were made to simulate the real postures utilized by sit-skiing para-athletes, the laboratory conditions may not correspond to all conditions that athletes face in a racing situation. In a recent study by Rosso et al. (2017), it was, however, concluded that natural uphill (2.5°) skiing and ergometer skiing were comparable from a force production and muscle activation perspective. It remains to be studied how the sitting position affects cross-country skiing in downhills and curves where also balance control is very important.

Based on all the posture-dependent differences at stage three in this study, the disadvantage of using the “knee-high” instead of the “kneeing” posture could be over 15% at this level of intensity. In the percentage-system applied by the International Paralympic Committee, the compensation for an LW10 athlete compared to an LW12 athlete is 14% (International Paralympic Committee, 2020a). In this study, the difference between the two postures was more that this 14% compensation despite the fact that the physical condition of the athlete was the same in both postures. Therefore, an LW10 athlete forced to use the “knee-high” posture could suffer an additional disadvantage compared to an LW12 athlete using the “kneeing” posture due to their more severe impairment. Furthermore, athletes in the lower classes may also be able to use the “kneeing” posture and the compensation between classes LW10 and LW11 for example is only 8% (International Paralympic Committee, 2020a). The decision to use able-bodied athletes in this study was made due to high variety in level of impairment among disabled skiers that could confound the interpretation of the results. Moreover, the “kneeing” posture would be difficult or impossible for athletes in lower LW classes to perform. However, further research is needed to establish posture-dependent differences in sit-skiing economy among actual sit-skiers. For example, this could be possible by using athletes in higher LW classes only.

Practical Applications

In previous studies concerning traditional cross-country skiing (Mahood et al., 2001; Mikkola et al., 2010; Ainegren et al., 2013) it has been concluded that good skiing economy is a crucial factor for succeeding in competitions. Given that observation and those of the present study, it can be recommended for coaches and sit-skiers to adopt a "kneeing" posture used in the present study. It is important to note, however, that not all sit-skiers are able to use the "kneeing" posture due to their impairment. In any case even a small use of trunk muscles during skiing may assist to train those important trunk muscles. Knee-high position seems to inhibit the use of the trunk even in non-disabled athletes so this position should be avoided if possible. Whether the current classification process and percentage-system accounts for this properly should be studied with disabled athletes.

DATA AVAILABILITY STATEMENT

Due to restrictions set by the ethics committee that approved this work, the datasets generated for this study will not be made publicly available. Requests to access these datasets should be directed to Vesa Linnamo, vesa.linnamo@jyu.fi.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the University of Jyväskylä. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

KL, WR, JA, and VL planned the study. KL and WR conducted the measurements. KL analyzed the data. All authors participated in the article writing.

ACKNOWLEDGMENTS

We would like to thank all the athletes that participated in the project.

REFERENCES

Ainegren, M., Carlsson, P., Tinnsten, M., and Laaksonen, M. S. (2013). Skiing economy and efficiency in recreational and elite cross-country skiers. *J. Strength Cond. Res.* 27, 1239–1252. doi: 10.1519/JSC.0b013e31824f206c

Bernardi, M., Janssen, T., Bortolan, L., Pellegrini, P., Fischer, G., and Schena, F. (2013). Kinematics of cross-country sit skiing during a paralympic race. *J. Electromyogr. Kinesiol.* 23, 94–101. doi: 10.1016/j.jelekin.2012.07.004

Gastaldi, L., Pastorelli, S., and Frassinelli, S. (2012). A biomechanical approach to paralympic cross-country sit-ski racing. *Clin. J. Sport Med.* 22, 58–64. doi: 10.1097/JSM.0b013e31824202d3

Holmberg, H-C., Lindinger, S., Stöggl, T., Björklund, G., and Müller, E. (2006). Contribution of the legs to double-poling performance in elite cross-country skiers. *Med. Sci. Sports Exerc.* 38, 1853–1860. doi: 10.1249/01.mss.0000230121.83641.d1

Holmberg, H-C., Lindinger, S., Stöggl, T., Eitzlmair, E., and Müller, E. (2005). Biomechanical analysis of double poling in elite cross-country skiers. *Med. Sci. Sports Exerc.* 37, 807–818. doi: 10.1249/01.MSS.0000162615.47763.C8

International Paralympic Committee (2020a). *IPC Nordic Skiing Percentages Season 2014–2016,* Retrieved from: https://www.paralympic.org/nordic-skiing/downloads (accessed April 17, 2020).

International Paralympic Committee (2020b). *IPC Nordic Skiing Rules & Regulations 2018–2019*. Retrieved from: http://www.paralympic.org/nordic-skiing/rules-and-regulations/rules (accessed April 17, 2020).

International Paralympic Committee (2020c). *Nordic Skiing Classification*. Retrieved from: http://www.paralympic.org/nordic-skiing/rules-and-regulations/classification (accessed April 17, 2020).

International Paralympic Committee (2020d). *Winter Sports*. Retrieved from: http://www.paralympic.org/sports/winter (accessed April 17, 2020).

Mahood, N. V., Kenefick, R. W., Kertzer, R., and Quinn, T. J. (2001). Physiological determinants of cross-country ski racing performance. *Med. Sci. Sports Exerc.* 33, 1379–1384. doi: 10.1097/00005768-200108000-00020

Mikkola, J., Laaksonen, M., Holmberg, H–C., Vesterinen, V., and Nummela, A. (2010). Determinants of a simulated cross-country skiing sprint competition using V2 skating technique on roller skis. *J. Strength Cond. Res.* 24, 920–928. doi: 10.1519/JSC.0b013e3181cbaaaf

Rapp, W., Lindinger, S., Lappi, T., Ohtonen, O., and Linnamo, V. (2013). "Force production, balance control and muscle activation in different sitting positions – pilot study for disabled sit sledge cross-country skiers," in *Book of Abstracts: 6th International Congress on Science and Skiing* (St. Christoph: University of Salzburg), 53.

Rosso, V., Gastaldi, L., Rapp, W., Lindinger, S., Vanlandewijck, Y., and Linnamo, V. (2017). Biomechanics of simulated versus natural cross-country sit skiing. *J. Electromyogr. Kinesiol.* 32, 15–21. doi: 10.1016/j.jelekin.2016.11.002

Rosso, V., Linnamo, V., Rapp, W., Lindinger, S., Vanlandewijck, Y., and Gastaldi, L. (2016). "Trunk kinematics during cross country sit-skiing ergometry," in *2016 IEEE International Symposium on Medical Measurements and Applications Proceedings* (Rome), 149–154.

Schillinger, F., Rapp, W., Hakkarainen, A., Linnamo, V., and Lindinger, S. (2016). "A descriptive video analysis of classified Nordic disabled sit-skiers during the Nordic World Championships 2013," in *Science and Nordic Skiing III*, eds A. Hakkarainen, V. Linnamo, and S. Lindinger, 173–180.

Smith, G. A., Fewster, J. B., and Braudt, S. M. (1996). Double poling kinematics and performance in cross-country skiing. *J. Appl. Biomech.* 12, 88–103. doi: 10.1123/jab.12.1.88

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.

frontiers in Sports and Active Living

REVIEW
published: 28 April 2020
doi: 10.3389/fspor.2020.00034

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Exercise in Sub-zero Temperatures and Airway Health: Implications for Athletes With Special Focus on Heat-and-Moisture-Exchanging Breathing Devices

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Edited by:
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Reviewed by:
Leif Hilding Bjermer, Lund University, Sweden
Martin Faulhaber, University of Innsbruck, Austria

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Specialty section:
This article was submitted to Sports Science, Technology and Engineering, a section of the journal Frontiers in Sports and Active Living

Received: 07 August 2019
Accepted: 18 March 2020
Published: 28 April 2020

Citation:
Hanstock HG, Ainegren M and Stenfors N (2020) Exercise in Sub-zero Temperatures and Airway Health: Implications for Athletes With Special Focus on Heat-and-Moisture-Exchanging Breathing Devices. Front. Sports Act. Living 2:34. doi: 10.3389/fspor.2020.00034

Asthma is highly prevalent among winter endurance athletes. This "occupational disease" of cross-country skiers, among others, was acknowledged during the 1990s, with the pathogenesis attributed to repeated and prolonged exposure to cold, dry air combined with high rates of ventilation during exercise. Nevertheless, more than 25 years later, the prevalence of asthma among Scandinavian cross-country skiers is unchanged, and prevention remains a primary concern for sports physicians. Heat-and-moisture-exchanging breathing devices (HMEs) prevent exercise-induced bronchoconstriction in subjects with pre-existing disease and may have potential as a preventative intervention for healthy athletes undertaking training and competition in winter endurance sports. Herein we firstly provide an overview of the influence of temperature and humidity on airway health and the implications for athletes training and competing in sub-zero temperatures. We thereafter describe the properties and effects of HMEs, identify gaps in current understanding, and suggest avenues for future research.

Keywords: asthma, airway inflammation, exercise, exercise-induced bronchoconstriction (EIB), cross-country skiing, winter sports

INTRODUCTION

Athletes training and competing outdoors will, most likely, be periodically exposed to cold, and sometimes sub-zero air. In fact, around 4 million people live in the Arctic region (Larsen and Fondahl, 2015) and many more are intermittently exposed to sub-zero temperatures during work and leisure. Exposure to cold air is associated with increased morbidity and mortality in the general population (Rocklöv and Forsberg, 2008). Possible explanations for these observations include increased bacterial survival leading to more airway infections (Handley and Webster, 1995), chilling of the nasal epithelium leading to inhibition of respiratory defense against pathogens (Eccles, 2002), cutaneous vasoconstriction leading to increased blood pressure and cardiac load (Cheng and Su, 2010), increased coagulation (Hampel et al., 2010) and bronchoconstriction leading to airway obstruction (Koskela and Tukiainen, 1995).

Studies from Finland show that up to 50% of the population report at least some cold-related symptoms (Harju et al., 2010; Näyhä et al., 2011) and that symptoms appear to be more common in women than men (Näyhä et al., 2011). A recent study found that experimental exposure to sub-zero temperatures at rest and when performing light exercise elicited 50 distinct symptoms among healthy subjects and patients with obstructive lung disease (Sjöström et al., 2019). Respiratory symptoms are also very common among children undertaking physical activity in cold temperatures (Rasi et al., 2017). Potentially for these reasons, up to one third of asthmatic individuals report avoidance of outdoor activities during cold spells (Millqvist et al., 1987). Thus, cold climates can present a challenge to facilitate physical activity from a public health perspective, and moreover individuals who habitually undertake physical activity in cold environments may experience airway symptoms and/or morbidity as a result of their training.

Winter endurance athletes, such as cross-country skiers, frequently undertake prolonged exercise in cold environments and report an increased prevalence of airway symptoms, bronchial hyper-reactivity and asthma (Carlsen et al., 2008). Asthma is a heterogeneous chronic inflammatory disease of the airways, characterized by recurrent episodes of bronchial constriction and airflow limitation that presents with symptoms such as cough, wheezing, and breathlessness. In Sweden, the prevalence of asthma among adolescents and young adults aged 16–24 years is around 9% (Wennergren et al., 2010). In 1994, 15% of 299 Swedish athletes from upper secondary school cross-country ski teams and the Swedish army reported physician-diagnosed asthma (Larsson et al., 1994). More recently, asthma prevalence among Swedish elite cross-country skiers has been estimated at 29–35%, with onset typically occurring during adolescence (Norqvist et al., 2015; Eriksson et al., 2018).

Two major mechanisms may explain the increased prevalence of exercise-induced asthma in winter endurance athletes. The airways condition inspired air to 37°C and 100% relative humidity (equivalent to 44 $mg \cdot L^{-1}$ H_2O) which leads to evaporative water loss from the airway surface (Kippelen et al., 2018). This evaporative water loss cools the mucosa, leading to vasoconstriction, reactive hyperemia, vascular leakage, and edema. Meanwhile, dehydration of the airway mucosa increases osmolarity of the periciliary fluid and stimulates the release of mediators that trigger smooth muscle contraction (Anderson and Daviskas, 2000; Anderson and Kippelen, 2008). The physiological stimuli of mucosal cooling and dehydration are likely to be exacerbated by low temperatures, dry climates, and prolonged, high rates of ventilation, each hallmarks of the training environment for winter endurance sports. Heat-and-moisture-exchanging breathing devices (HMEs), discussed in detail in the latter part of this article, may thus directly intervene with the proposed pathway of airway injury among winter endurance athletes.

The aim of this narrative review is therefore twofold; to first provide an overview of pathophysiological responses to exercise in sub-zero temperatures, and secondly, to review the potential of HMEs to prevent airway pathophysiological responses to cold air exercise. Throughout we maintain a focus on the implications for athletes and practitioners undertaking training and competition in these environments and highlight gaps in current knowledge with potential for translation into practical recommendations.

PATHOPHYSIOLOGY OF EXERCISE-INDUCED ASTHMA IN COLD WEATHER ATHLETES

Conditioning of Inspired Air

The nasal passage is an important structure which serves to condition inspired air to near-alveolar conditions. Nasal breathing appears to defend against airway cooling when inhaling sub-zero air (Griffin et al., 1982). Indeed, anthropologists have noted longer, narrower, nasal cavities in human populations native to cold, dry climates, compared to humans from hot and humid climates, suggesting an important role of the nasal cavity in warming and humidifying cold, dry air (Noback et al., 2011). While nasal breathing is the norm in healthy individuals at rest, during exercise breathing patterns habitually switch to oronasal breathing at minute ventilation ($\acute{V}_E$) rates around 35 $L \cdot min^{-1}$ (Niinimaa et al., 1980). Oral breathing appears to be less efficient at conditioning inspired air, leading to lower inspired air temperatures (Griffin et al., 1982) and drying of the upper airway mucosa (Verma et al., 2006). A few individuals are able to maintain predominantly nasal breathing patterns even during high-intensity exercise and it would be interesting to investigate whether habitual breathing during exercise is associated with development of airway hyper-responsiveness. However, for the majority of individuals exercising at high to maximal exercise intensities, oronasal breathing predominates, which could in turn impair the ability of the airways to condition inspired air.

Thermal mapping of the airways indicates that room temperature air (26°C, 8.8 $mg \cdot L^{-1}$ H_2O) is warmed during tidal breathing to ∼32°C at the tracheal carina and 35.5°C in the subsegmental bronchi. At a $\acute{V}_E$ of 100 $L \cdot min^{-1}$, inspired air temperatures fall by ∼2°C at each location. Meanwhile, inhaled air at −18°C and 0 $mg \cdot L^{-1}$ H_2O reaches only 23°C at the carina and 31°C at the bronchial level (McFadden et al., 1985). Light to moderate-intensity exercise in −20°C elicits exhaled air at around 28–31°C and relative humidity >90% (Cain et al., 1990). Thus, it is reasonable to suggest that below certain sub-zero temperatures, the airways are unable to fully warm and humidify inspired air. The challenge to the airways to condition inspired air is further amplified at ventilatory rates typically attained during moderate to high-intensity exercise and exacerbated by oronasal breathing.

Quantification of Temperature and Humidity in Inspired Air

Decreases in environmental humidity and temperature present an additional challenge to the airways to adequately condition inspired air. During hyperpnea, which naturally occurs during high-intensity exercise, heat and water losses further increase, especially in the upper airways, causing airway dehydration and inducing a hypertonic periciliary fluid (Daviskas et al., 1991). Moreover, cold air holds less water vapor, so is dry by default compared to temperate air and may exacerbate airway dehydration. Magnus' exact formula (Rindert, 1993) may be used to derive the absolute humidity for a given temperature, relative humidity, and pressure. **Figure 1** illustrates the challenge for the

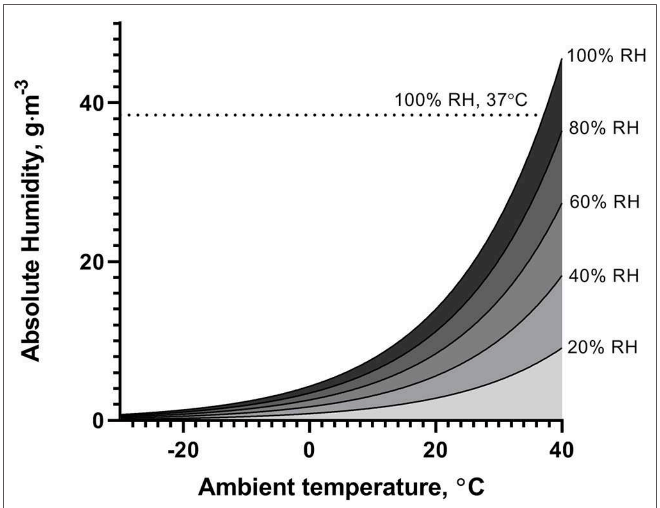

FIGURE 1 | Illustration of absolute humidity of ambient air at temperatures between −30 and 40°C, for different levels of relative humidity (RH).

airways to heat and humidify inhaled air to near core temperature and saturated with water vapor (absolute humidity = 38.5 g/m^3 at 37°C and 100% RH), at different ambient temperatures and levels of relative humidity (assuming ambient pressure = 1,013 hPa).

Effects of Whole-Body Exposure to Cold Air

Individuals participating in winter endurance sports not only inhale cold, dry air but experience whole-body exposure to sub-zero environments during training and competition. Controlled environment conditions generated by environmental chambers permit simulation of the training environment and experimental investigation of systemic physiological responses to exercise in cold climates. To date, exposure studies have frequently focused on lung function and elucidating mechanisms, often using isolated cold and/or dry air inhalation as an experimental stimulus (Strauss et al., 1977; Deal et al., 1979; Eiken et al., 1989). However, airway obstruction has been shown to be more pronounced when the face (Koskela and Tukiainen, 1995; Josenhans et al., 2011) or nose (Fontanari et al., 1996, 1997) are exposed to cold air among both healthy and asthmatic subjects. This indicates that whole-body exposure, as opposed to isolated hyperpnea of cold, dry air, may be a preferred approach to evaluate airway effects of cold air exposure as well as systemic physiological responses to cold. Furthermore, little distinction in the literature has been made between "cold" air of different temperatures, with studies investigating airway responses to cold air spanning a 50°C temperature range (10 to −40°C) (Cain et al., 1990; Eschenbacher et al., 1992). With winter sports in mind, we herein focus on studies that have investigated airway and physiological effects of whole-body exposure to sub-zero air within typical temperature ranges experienced by winter endurance athletes; that is, 0°C to around −20°C.

Effects of Cold Air on Lung Function

It has been shown that even 5–10 min of whole-body *resting* exposure to −17°C may trigger acute decreases in forced expiratory volume in 1 s (FEV1), the classical measurement of airway obstruction, in both healthy subjects and patients with obstructive lung disease (asthma or chronic obstructive pulmonary disease (COPD) (Koskela and Tukiainen, 1995; Koskela et al., 1996). It has then been consistently observed that exercising in sub-zero temperatures induces bronchial obstruction in subjects with respiratory disease (Koskela et al., 1994, 1998; Stensrud et al., 2007). When *healthy* subjects perform physical activity to exhaustion, acute bronchial obstruction has also been detected at sub-zero temperatures (Therminarias et al., 1998; Kennedy and Faulhaber, 2018), but the results are inconsistent, with lower-intensity protocols revealing no effect on pulmonary function (Pekkarinen et al., 1989; Chapman et al., 1990). Discrepancies in the current literature may be explained not only by heterogeneity in exercise intensity, duration and modality but potentially also by differences in temperature and relative humidity across a relatively small number of studies (**Table 1**).

Among non-asthmatic skiers, up to 75% have returned positive responses to methacholine challenge (Karjalainen et al., 2000). Furthermore, a higher rate of positive methacholine challenge arose during winter in competitive speed skaters (Kurowski et al., 2018a) and methacholine reactivity was increased after the coldest period of the year in cross-country skiers (Heir and Larsen, 1995). However, some of the hallmarks of airway inflammation observed in cross-country skiers are not consistent with those of atopic asthma, eosinophilic asthma or traditional models of exercise-induced bronchoconstriction, in line with the suggestion that "sports asthma," including that exacerbated by training in cold and dry air, has a distinct phenotype (Couto et al., 2015). Potentially for this reason, classical screening tests such as EVH have been shown to have poor agreement with a field test for exercise-induced bronchoconstriction (EIB) induced by exercise in cold environments, and it has been suggested that more research may be required to explore the best types of screening test for EIB in cold weather athletes (Kennedy et al., 2019).

Effects of Cold, Dry Air on Airway Inflammatory Responses

A handful of studies have shown that elite cross-country skiers, including those with and without asthma, display markers of chronic airway inflammation and damage to the airway epithelial lining. These studies report increased bronchoalveolar and/or mucosal infiltration of eosinophils, neutrophils, macrophages, mast cells, and lymphoid aggregates in athletes training in cold climates compared to healthy controls, but fewer eosinophils and mast cells and more neutrophils than in subjects with asthma (Sue-Chu et al., 1998, 1999; Karjalainen et al., 2000). A more recent longitudinal study of female cross-country skiers over the course of a training season reported an increase in sputum eosinophils and lymphocytes between the beginning of the training year (late spring) and the peak of the winter competitive

TABLE 1 | Experimental studies that have employed environmental chamber models to examine acute effects of short-term, whole-body exposure to sub-zero temperatures on lung function and other physiological variables.

References	Subjects	Temperature (°C)	Humidity	Duration (minutes)	Exercise intensity	Outcome
Pekkarinen et al. (1989)	Healthy males, $n = 20$	−20	∼50% RH	8–17	70–75% of HR_{max}	No effect on FVC, FEV_1, PEF, MEF
Chapman et al. (1990)	Healthy, $n = 12$	−11	<2% RH	30	80% of $\dot{V}O_{2max}$	No effect on pulmonary function indices
Koskela et al. (1994)	Asthma, $n = 19$	−20	Not reported	10	≥70% of HR_{max}	FEV_1 ↓
Koskela and Tukiainen (1995)	Healthy, $n = 15$, and asthma, $n = 10$	−17	Not reported	10	Rest	FEV_1 ↓ both groups
Koskela et al. (1996)	COPD, $n = 20$, and healthy, $n = 10$	−17	<1.75 mg/L	5–10	Rest	FEV_1 ↓ both groups
Koskela et al. (1998)	COPD, $n = 14$	−19	Not reported	10	Until exhaustion	FEV_1 ↓ Exercise duration ↓
Therminarias et al. (1998)	Healthy well-trained males, $n = 8$	−10	Not reported	30	Until exhaustion	FEV_1 and FEF75 ↓
Stensrud et al. (2007)	Exercise-induced asthma, $n = 20$	−18	39% RH	8	≥95% of HR_{max}	$\dot{V}O_{2peak}$ running speed, FEV_1°↓
Kennedy and Faulhaber (2018)	Healthy females, $n = 17$	0 to −20	40% RH	28	Until exhaustion	FEV_1 ↓

FEF75, Forced expiratory flow at 75% forced vital capacity; FEV_1, Forced expiratory volume in 1 s; FVC, Forced vital capacity; HR_{max}, Maximal heart rate; MEF, Maximal expiratory flow; PEF, Peak expiratory flow; $\dot{V}O_{2peak}$, Peak oxygen uptake; $\dot{V}O_{2max}$, Maximal oxygen uptake.

ski season (Kennedy et al., 2016). A mixed cohort of speed skaters and swimmers also presented with a similar inflammatory cytokine profile in exhaled breath condensate as that seen in asthmatics (Kurowski et al., 2018b). Furthermore, baseline TNF-α in exhaled breath condensate was positively correlated with percentage decreases in FEV_1 following exercise challenge for both athletes during a hard training period and asthmatic subjects (Kurowski et al., 2018b). Among speed skaters reporting exercise-induced respiratory symptoms, IL-1RA was elevated during the winter training period compared to asymptomatic athletes (Kurowski et al., 2018a). Together these observations suggest a multifactorial inflammatory profile may develop during winter training in athletes that may be associated with symptoms and/or lung function.

However, very few studies have examined acute inflammatory responses to exercise in cold under standardized environmental conditions in either individuals with asthma or healthy subjects. Performing 2 h light exercise in −23°C has been shown to increase number of granulocytes and macrophages in the lower airways in healthy subjects (Larsson et al., 1998). However, as highlighted by Bonsignore and colleagues as long ago as 2003, there remains a gap in current knowledge about how acute exercise sessions performed in cold may acutely influence markers of inflammation local to the airways (Bonsignore et al., 2003). Systemic immune responses are typically not influenced by exercise in cold (Castellani et al., 2002), however, exercise duration and intensity are known to substantially influence immune responses to exercise, with prolonged, moderate-intensity exercise provoking greater *in vivo* immune perturbations than short, high-intensity exercise (Diment et al., 2015). On the other hand, it has been observed that bronchial hyper-reactivity to methacholine increases in association with volume of physical activity at higher exercise intensities (>90% maximal heart rate) (Heir and Larsen, 1995), and anecdotal reports from coaches and athletes have informed us that elite skiers tend to report respiratory symptoms more frequently after sprint competitions (typically 3–4 min duration at near-maximal intensities). Therefore, it would be pertinent to investigate whether inflammatory and immune markers local to the airways are acutely influenced by short, high-intensity exercise (i.e., near-maximal $\dot{V}_E$) or prolonged, moderate-intensity exercise (i.e., high area-under-curve for $\dot{V}_E$).

Effects of Cold, Dry Air on Airway-Related Symptoms

Upper and lower respiratory symptoms are common among winter athletes (Svendsen et al., 2016; Valtonen et al., 2019) with as many as 80% reporting sporadic exercise-associated respiratory symptoms (Kurowski et al., 2018a). It has also been reported that occurrence of upper respiratory infections increases in the general population with cold temperature and low humidity (Mäkinen et al., 2009), which may partially explain increased symptom reports during winter. Although a proportion and perhaps indeed a majority of symptoms reported may be associated with viral upper respiratory tract infections (Spence et al., 2007; Valtonen et al., 2019), it is clear that not all symptoms are attributable to infectious causes (Rundell et al., 2001), particularly with regard to exercise-associated symptoms. For example, increased reporting of cough in cross-country skiers during the winter competitive season has been associated with sputum neutrophils and total yearly training (Kennedy et al., 2016), suggesting a direct localized association with both airway immune cells and training stress.

Cold Effects on Performance

From a performance perspective, cross-country skiing double-poling performance has been shown to decline at −15 vs. 6°C whilst wearing a standard racing suit (Wiggen et al., 2016). Running time to exhaustion in cross country skiers has also been reported as shorter at −14°C than −4 and 1°C when wearing a standard cross-country racing suit (Sandsund et al., 2012). Considering both studies together, core temperature typically increases during exercise at −14 to −15°C but potentially to a lesser extent than at warmer temperatures (−9 to 20°C). Colder environments appear to produce greater reductions in skin temperature during exercise. Neither study found differences in $\dot{V}O_2$ nor $\dot{V}_E$ during maximal exercise tests across a broad range of environmental conditions (−15 to 20°C), but power output was lower during the first 8 min of the 20-min double poling test at −15°C compared to 6°C, suggesting that a reduction in skin temperature may lead to muscular cooling and reduced exercise economy (Wiggen et al., 2016). Muscular cooling may also be associated with increased risk of injury (Scott et al., 2016). Together these results suggest that in cross-country skiers without asthma, ventilatory rates and oxygen uptake are not significantly affected during high-intensity exercise at −15°C (Wiggen et al., 2016).

TOWARD TEMPERATURE AND HUMIDITY THRESHOLDS FOR AIRWAY PATHOPHYSIOLOGICAL RESPONSES

Assuming that the increased risk of developing asthma among winter endurance athletes is due to repeated and prolonged inhalation of cold and dry air, a pertinent question arising from athletes, coaches and organizations in winter sports is whether specific ambient temperature and/or humidity thresholds can be defined below which airway damage is likely to occur during training or competition. From an epidemiological perspective, the threshold temperature for presentation of cold-related respiratory symptoms at a population-level is at sub-zero temperatures (−7 to −18°C) and slightly higher among subjects with lung disease (Harju et al., 2010).

The relative importance of inhaled air temperature vs. humidity on airway responses to the cold remains unclear. Low water content of inhaled air appears to be a stronger inducer of exercise-induced asthma than low temperature, at least at non-freezing temperatures (Hahn et al., 1984; Anderson et al., 1985; Eschenbacher et al., 1992). However, hyperpnea of sub-zero dry air has been shown to induce greater airway obstruction in asthmatic subjects compared to inhalation of dry air at room temperature (Zawadski et al., 1988), suggesting temperature itself factor that could exacerbate bronchoconstriction. It has even been reported that cold, damp air may elicit more symptoms in patients with asthma than cold, dry air (Millqvist et al., 1987). Taken together, there is a lack of agreement on critical thresholds for airway health risks, both in asthmatic and non-asthmatic subjects, with respect to inhaled air temperature and humidity; particularly for elite winter endurance athletes undertaking exercise in cold, dry conditions.

Anecdotally, it could be expected that training and competition temperatures in winter sports are frequently below 0°C but rarely below −20°C. Thus, perhaps the first important question for those participating in recreational activity and competitive sport in sub-zero climates is whether the challenge to the airways to humidify air varies substantially within this temperature range to increase risk of airway injury or presentation of respiratory symptoms. It is possible that it is not just the absolute humidity but the rate of cooling and/or condensation of expired air in sub-zero temperature that plays an important role in determining this.

Temperature Limits for Competitions

The Federation Internationale de Ski (FIS) rules for international competition at the time of writing state that if the temperature is below −20°C at the coldest part of the course, a competition should be postponed or canceled. In the case of other challenging weather conditions such as strong winds or high humidity (as well as high temperature or heavy snowfall) the Jury may also decide to postpone or cancel the competition. For so-called "popular" competitions, FIS rules also recommend additional precautions, for example to provide recommendations regarding cold weather protection if the temperature is forecast to be between −15 and −25°C, and cancellation if the temperature in a major portion of the course is expected to be −25°C or below (Federation Internationale de Ski, 2018). It has been suggested via the FIS Medical Committee that temperature thresholds should be higher for long-distance races (>30 km, −16°C) than for shorter distances (<30 km, −18°C) and sprints (−20°C), and higher (−12°C) for children under 14 years (Lereim, 2007). Although such regulations may have been adopted by local or national organizations, these recommendations have not been implemented in international competitions to date. The International Biathlon Union (IBU) rules at the time of writing state that competitions should not be started if the air temperature is below −20°C at the coldest part of the site, but that if it is colder than −15°C then wind chill and humidity must be considered (International Biathlon Union, 1998).

Are Current Temperature Limits Appropriate?

Most winter endurance sport governing bodies recommend lower temperature limits for competition. However, despite earlier commentaries on the potential respiratory health risks of undertaking competitions in very cold and dry climates (Kippelen et al., 2012; Sue-Chu, 2012), few explicitly cite concerns regarding airway health as a major rationale. Collectively, rules stipulated by governing bodies in winter endurance sports suggest little consensus in "safe" temperatures for competition for elite or amateur athletes.

It is clear that temperatures above the present limits stipulated by governing bodies may induce bronchoconstriction in subjects with asthma. Protection of the airways under such conditions would therefore seem warranted and it is notable that heat-moisture exchanging breathing devices are not prohibited in competition. Of further interest is the question about whether current competition temperature thresholds are safe for healthy athletes without asthma. During exercise at −23°C, cellular responses associated with airway inflammation have been observed in healthy individuals (Larsson et al., 1998). Airway inflammatory responses as well as epithelial injury have potential to underpin the development of asthma in at-risk individuals, but the existence of sub-clinical airway inflammation arising from exercise in cold in individuals without asthma is not well-defined, let alone threshold temperatures at which such responses could occur. Given development of asthma among winter endurance athletes typically presents during adolescence and later than in reference populations (Eriksson et al., 2018), there is also a need to investigate whether adolescents and young athletes are in need of more conservative guidelines to reduce risk of airway injury.

Heat-and-Moisture-Exchanging Breathing Devices

Heat and moisture exchangers (HMEs) are simple and generally inexpensive tools that may offer protection to the airways from the potentially damaging effects of heavy exertion in sub-zero conditions. On the market there are essentially three different types of HME design, all with the common feature of a filter where exchange of inspiratory and expiratory air can take place. A representative selection of the three designs of HME is shown in **Figure 2**.

The first design of HME is held firmly with the mouth (Lungplus Info AB, Hörby, Sweden) and does not cover the nose, which then will maintain its usual function as heat exchanger and humidifier of inspired air. The second design of HME consists of a mask (Air Trim, Vapro Produktutveckling AB, Västerås, Sweden) covering the skin surface around both nose and mouth. This type of HME is held in place against the skin by means of a strap which is tensioned around the back of the head. The third type of HME has the filter fixed in a tube of some type of textile that is threaded over the head and covers most of the face including nose, mouth and neckline (Jonaset 0602, Suojalaite OY, Helsinki, Finland). The principle of a HME is that its inner surfaces and filters are heated and moistened by the exhaled air. The filter also constitutes a barrier that prevents the mixing of residual exhaled air with ambient air so that the volume and the surface inside the HME is prevented from being cooled and dehumidified with ambient air during the short time between exhalation and inhalation. Upon inhalation, cold and dry ambient air will therefore be able to be heated and moistened both by the filter and the remaining exhaled volume inside the HME. Differences in HME filter area, mesh density, and remaining expiratory volume should lead to differences in the ability to warm and humidify inhaled air. Some degree of heat impact from the friction between gas molecules and the filter is also conceivable but probably relatively small in context. The intended functionality of an HME is thus to provide a pre-station where cold and dry ambient air is partially warmed and humidified before inspiration and thus before the cold air reaches the upper airways.

Influence of HME on Breathing and Inspired Air Composition

The use of an HME may have both positive and negative consequences for the user which may be affected by both the type of HME and intensity of activity. HME filters are effective at warming air as it passes through the filter, especially when the source air is cold (Nisar et al., 1992). However, the remaining volume of exhaled air inside the HME constitutes an effective increase in dead space leading to a decrease and increase in inspiratory O_2 and CO_2 fractions, respectively (Campbell et al., 2000). Also, breathing through the filter may to some extent increase resistance to breathing. The volume of increased dead space varies with design and the manufacturer of HME, like probably the resistance to breathing, and the affected inspiratory gas fractions can be compensated for by the fact that the tidal volume is increased correspondingly to the increase in HME dead space. However, at high ventilations, such as the rates attained during high-intensity cross-country skiing, it may be difficult to increase the tidal volume further. Also, increased ventilation confers an increased energy cost for the respiratory muscles to further overcome the elasticity of the lung tissues and to drive the flow through the HME filter. However, since cold and dry air can cause bronchoconstriction, which leads to negative consequences such as increased airway obstruction, hypoventilation, and altered alveolar gas fractions, it would be interesting to investigate whether the sum of resistance from airways plus HME would be less than without using HME. Thus, prevention of bronchoconstriction with an HME would be positive for ventilation, pulmonary gas exchange, and energy cost of breathing.

HMEs Prevent Exercise-Induced Asthma

A handful of studies have demonstrated that HMEs can attenuate exercise-induced bronchoconstriction triggered by cold and/or dry air (**Table 2**). Despite heterogeneity in ambient/inspired air temperatures (23 to −25°C), humidity, exercise protocol intensity and duration, these observations suggest that use of HMEs may be an effective strategy for prevention of exercise-induced airway obstruction in patients with asthma exercising in cold and/or dry conditions. A common trait of these studies is that all used participants with asthma, with reductions in FEV_1 as the primary endpoint. Three studies reported protective effects of HMEs to attenuate reductions in FEV_1 after exercise in sub-zero climates (Nisar et al., 1992; Millqvist et al., 1995; Beuther and Martin, 2006), cool temperatures (Jackson et al., 2018) and dry, ambient temperatures (Brenner et al., 1980; Millqvist et al., 1995). In addition, breathing through unidirectional inspiratory and expiratory filters in a placebo mask (Millqvist et al., 1995), and use of a placebo filter (Beuther and Martin, 2006) did not attenuate bronchoconstriction compared to a no-mask condition, giving weight to the mechanism of heat-moisture exchange in the filter as the mode of protection imparted by the mask. It has been shown that the attenuation of bronchoconstriction achieved by use of an HME is comparable in magnitude to the protective effects imparted by pre-treatment with short-acting beta-2 agonists prior to exercise, and that combining the two strategies can fully prevent reductions in FEV_1 (Millqvist et al., 2000).

What About HMEs for Healthy Athletes?

While the case to consider HMEs as preventative tools for exercise-induced asthma may be relatively well-supported by present data, we are aware that many athletes without asthma may also utilize HMEs. Given the higher risk of developing exercise-induced asthma among elite winter endurance athletes, investigation of the potential of HMEs to attenuate asthma-like symptoms, bronchial obstruction, or other biomarkers of airway injury is warranted. To our knowledge, only a single study to

FIGURE 2 | Three representative types of HME: Lungplus (upper left), AirTrim (lower left), and Jonaset 0602 (right).

date has set out to evaluate potential prophylactic effects of HMEs to prevent airway damage or asthma in healthy athletes. Following a high-intensity exercise bout in −20°C, without use of an HME, Frischhut et al. (2020) reported post-exercise decreases in FVC and FEV_1 in healthy athletes. HME usage attenuated these responses, and also resulted in fewer respiratory symptoms (Frischhut et al., 2020).

Anecdotal evidence suggests that HMEs are routinely used not only by individuals with asthma but also by otherwise healthy individuals training in very cold environmental conditions. It appears less common that healthy athletes utilize HMEs for high-intensity training sessions or in competition. The rationale underpinning this choice requires further investigation but could include improved comfort during training, reduction in respiratory symptoms and/or a belief that HMEs are protective for their airway health.

Given the higher risk of developing exercise-induced asthma among elite winter endurance athletes, investigation of the potential of HMEs to attenuate asthma-like symptoms, bronchial obstruction, or other biomarkers of airway injury is warranted. To our knowledge, no studies to date have evaluated potential prophylactic effects of HMEs to prevent airway damage or asthma in healthy athletes.

At present, a conservative approach may suggest that there is little risk for healthy athletes to use HMEs during training, but potentially high reward if HMEs are able to minimize airway injury and symptoms during exercise in very cold or dry environments. Nevertheless, avoidance of HME utilization by healthy athletes may occur for a multitude of reasons. Athletes may experience or perceive increased resistance to breathing and become concerned that this could impair their ability to perform in races, or complete high-intensity sessions as planned. Discomfort may occur if water vapor begins to freeze around the edges of the HME or around the filter area, and poor fit may become a distraction during training. Whilst a couple of studies suggest that healthy individuals can use a HME without discomfort or reduction in performance (Eiken et al., 1989; Seifert et al., 2017), it is likely that there is a large variation in comfort, fit and resistance to breathing among current, commercially-available HMEs. It is also possible that healthy athletes do not see a benefit to using HMEs, although, a recent study demonstrated that use of an HME during sprint exercise in −9°C attenuated the performance deficit seen without a HME in a cold environment; sprint performance in −9°C with a HME was similar to performance in room temperature (Seifert et al., 2017). Qualitative work could provide insight into current attitudes toward HME use in winter endurance athletes and inform manufacturers about whether current models are fit for purpose.

When Should HMEs Be Used?

With regard to recommendations for use of HMEs, many questions remain regarding temperature and/or humidity thresholds as well as exercise intensities at which use of HMEs may (or may not) be recommended for athletes with and without asthma. Numerous coaches and officials working in these sports have made a plea to us as sports physicians and scientists to recommend temperature and humidity thresholds below which risk of airway injury is substantially increased in junior and senior athletes, and further to provide information about whether

TABLE 2 | Studies showing that HMEs attenuate exercise-induced bronchoconstriction.

References	Temperature (°C)	Humidity	Duration (minutes)	Exercise intensity/ ventilation rate	Main finding
Beuther and Martin (2006)	−15 to −25 Isolated breathing of sub-zero air	Not reported	10	85% $\dot{V}O_{2max}$	Placebo: $\Delta FEV_1 = -19 \pm 4.9\%$ HME: $\Delta FEV_1 = -4.3 \pm 1.6\%$ fall in FEV_1
Nisar et al. (1992)	−13 Isolated breathing of sub-zero air	Not reported	6	75% $\dot{V}O_{2max}$	No HME: $\Delta FEV_1 = -22\%$ (−13 to −51%) HME: $\Delta FEV_1 = -10\%$ (0 to −26%)
Millqvist et al. (1995)	−10 Whole body exposure	Not reported	3 × 6	50–150 W	Study A, $n = 9$ No HME: $\Delta FEV_1 = -36\%$ HME: $\Delta FEV_1 = -11\%$ HME "protective effect" = 70% (range 19–100%) Two women could not complete protocol without HME Study B $n = 5$ HME "protective effect" = 74% Placebo mask with one-directional filters (no heat-moisture exchange), protective effect = 14%
Millqvist et al. (2000)	−10 Nasal clips to prevent nasal breathing	Not reported	3 × 6	Incremental 30–150 W	No HME: $\Delta FEV_1 = -27\%$ HME: $\Delta FEV_1 = -12\%$ Beta-2-agonist: $\Delta FEV_1 = -7\%$ HME+beta-2-agonist: ΔFEV_1 = None
Jackson et al. (2018)*	8 Whole body exposure	20% RH	6	80% PPO	HME: $\Delta FEV_1 = -6.0\%$, SHAM: $\Delta FEV_1 = -9.5\%$, No HME: $\Delta FEV_1 = -13.0\%$, $p = 0.03$ between HME and No HME.
Gravelyn et al. (1987)	22	0 mg $H_2O{\cdot}L^{-1}$	5	60–70 $L{\cdot}min^{-1}$	No HME: 300% increase in sRaw after hyperpnea with dry air HME: 7% increase in sRaw after hyperpnea
Brenner et al. (1980)	23	26% RH	6	90% HR_{max}	No HME: $FEV_1 = 66 \pm 6$ of individuals' (pre-exercise) baseline, 6 min after exercise HME: $FEV_1 = 91 \pm 3\%$ of individuals' baseline
Frischhut et al. (2020)	−20 Whole body exposure	46.2% RH	8	90–95% HR_{max}	Winter athletes without asthma No HME: FVC −5.9%, FEV_1 −4.2% vs. pre-exercise baseline HME: FVC no reduction FEV1 no reduction

*Conference proceedings.

FEV_1, Forced expiratory volume in 1 s; HME, Heat and moisture-exchanging breathing mask; HR, Heart rate; PPO, Peak power output; RH, Relative humidity; sRaw, Specific airways resistance; $\dot{V}O_2max$, Maximum oxygen uptake; W, Watts.

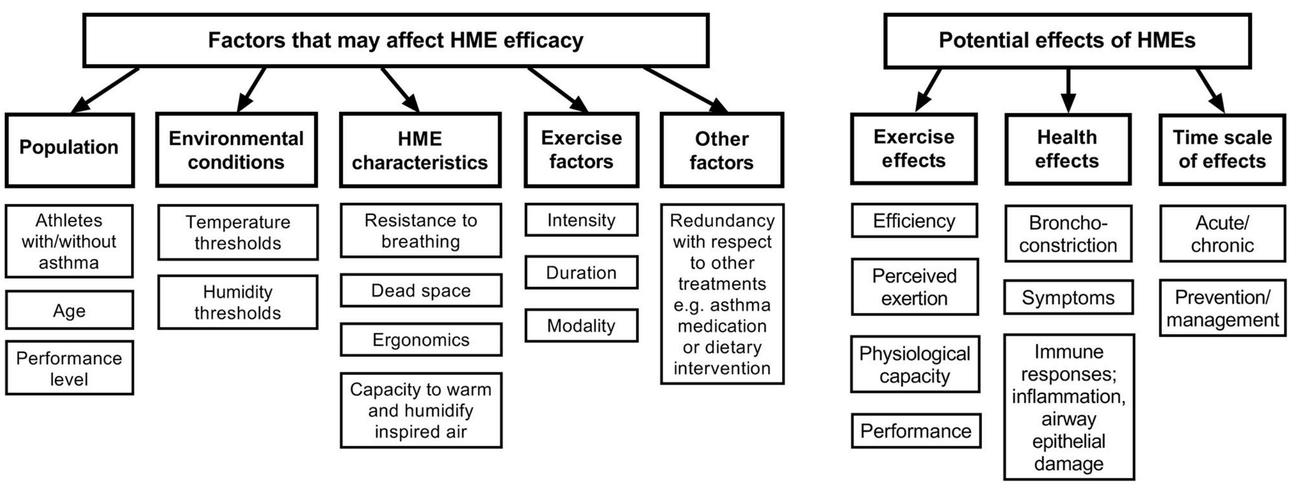

FIGURE 3 | Conceptual model of potential effects and interactions of HME use by athletes and exercising populations.

HMEs are sufficient to counteract potential detrimental effects on the airways of healthy athletes during exercise in the cold. **Table 1** summarizes the existing evidence for occurrence of airway responses at a range of sub-zero temperatures, and thus could be used to suggest thresholds below which use of HMEs might be appropriate for the healthy athlete, whereas **Figure 3** outlines potential effects of HMEs as well as factors to consider that may affect HME efficacy.

To summarize, there is a lack of knowledge at present about the extent of positive and negative effects of HME use, precisely with respect to their capacity to heat and humidify inhaled air, the resistance they pose to breathing and effects they have on athletes' ventilation, energy cost and performance. Given their observed effects on FEV_1 after exercise challenge, current data suggests HMEs have potential to mitigate exercise-induced asthma. If performance capacity via discomfort, distraction or breathing resistance remains a concern, utilization of an HME during the warm-up only could be worth considering, since warm-up may be beneficial in preventing subsequent EIB (Stickland et al., 2012); and because rapid transition from warm to cold environments (and back again) may provoke reactive hyperemia (Gilbert and McFadden, 1992). However, due to a paucity of data, such strategies would require further investigation. Future work should also examine the potential of HMEs to attenuate airway damage and inflammation as well as respiratory symptoms both in subjects with asthma and healthy individuals undertaking exercise training in sub-zero environments.

CONCLUSIONS

It is well-understood that exercise in cold and dry air can trigger airway inflammation and epithelial injury and may be associated with increased prevalence of airway hyper-responsiveness and asthma. Whilst this relationship has been understood for several decades, the prevalence of asthma in senior cross-country skiers in Scandinavia has not changed in this time, and so investigation of preventative strategies is warranted.

Current understanding suggests that repeated airway injury leads to development of inflammation and airway hyper-responsiveness, and that this process is exacerbated by cold and dry air. While FEV_1 is commonly used as a primary endpoint for studies in athletes with asthma, primary endpoints for the effect of cold air on the airways of healthy athletes have not been determined. Current temperature limits for competition in winter endurance sports make no specific reference to effects of the environment on the airways. A small body of evidence suggests that HMEs may attenuate exercise-induced bronchoconstriction, but existing data are discordant regarding environmental conditions where exercise may be harmful to the airways in healthy athletes or athletes who have already developed airway hyper-responsiveness. Further work is required to characterize temperature and humidity thresholds as well as exercise intensities and durations for which HME use may be recommended. Based on the limited evidence currently available, we suggest that for athletes with asthma, use of HMEs during training in sub-zero temperatures or dry environments could be a low-risk and high-return strategy to protect the airways. Athletes with healthy airways may be encouraged to use HMEs at sub-zero temperatures where airway discomfort arises, as a low-risk and *potential* prevention strategy against airway damage. However, further work is required to investigate the prophylactic potential of HMEs for both short-term attenuation of airway damage and respiratory symptoms in healthy athletes, as well as long-term prevention of asthma in winter endurance athletes.

AUTHOR CONTRIBUTIONS

HH, MA, and NS conceived the idea for the manuscript, drafted the manuscript, provided critical review, and approved the final version for publication.

REFERENCES

Anderson, S. D., and Daviskas, E. (2000). The mechanism of exercise-induced asthma is… *J. Allergy Clin. Immunol.* 103, 453–459. doi: 10.1067/mai.2000.109822

Anderson, S. D., and Kippelen, P. (2008). Airway injury as a mechanism for exercise-induced bronchoconstriction in elite athletes. *J. Allergy Clin. Immunol.* 122, 225–235. doi: 10.1016/j.jaci.2008.05.001

Anderson, S. D., Schoeffel, R. E., Black, J. L., and Daviskas, E. (1985). Airway cooling as the stimulus to exercise-induced asthma–a re-evaluation. *Eur. J. Respir. Dis.* 67, 20–30.

Beuther, D. A., and Martin, R. J. (2006). Efficacy of a heat exchanger mask in cold exercise-induced asthma. *Chest* 129, 1188–1193. doi: 10.1378/chest.129.5.1188

Bonsignore, M. R., Morici, G., Vignola, A. M., Riccobono, L., Bonanno, A., Profita, M., et al. (2003). Increased airway inflammatory cells in endurance athletes: What do they mean? *Clin. Exp. Allergy* 33, 14–21. doi: 10.1046/j.1365-2222.2003.01557.x

Brenner, A. M., Loren, M. L., Weiser, P. C., and Krogh, L. A. (1980). Effectiveness of a portable face mask in attenuating exercise-induced asthma. *JAMA J. Am. Med. Assoc.* 244, 2196–2198. doi: 10.1001/jama.1980.03310190048024

Cain, J. B., Livingstone, S. D., Nolan, R. W., and Keefe, A. A. (1990). Respiratory heat loss during work at various ambient temperatures. *Respir. Physiol.* 79, 145–150. doi: 10.1016/0034-5687(90)90014-P

Campbell, R. S., Davis, K., Johannigman, J. A., and Branson, R. D. (2000). The effects of passive humidifier dead space on respiratory variables in paralyzed and spontaneously breathing patients. *Respir. Care* 45, 306–12.

Carlsen, K. H., Anderson, S. D., Bjermer, L., Bonini, S., Brusasco, V., Canonica, W., et al. (2008). Treatment of exercise-induced asthma, respiratory and allergic disorders in sports and the relationship to doping: part II of the report from the Joint Task Force of European Respiratory Society (ERS) and European Academy of Allergy and Clinical Immunolog. *Allergy Eur. J. Allergy Clin. Immunol.* 63, 492–505. doi: 10.1111/j.1398-9995.2008.01663.x

Castellani, J. W., M., Brenner, I. K., and Rhind, S. G. (2002). Cold exposure: human immune responses and intracellular cytokine expression. *Med. Sci. Sport. Exerc.* 34, 2013–2020. doi: 10.1097/00005768-200212000-00023

Chapman, K. R., Allen, L. J., and Romet, T. T. (1990). Pulmonary function in normal subjects following exercise at cold ambient temperatures. *Eur. J. Appl. Physiol. Occup. Physiol.* 60, 228–232. doi: 10.1007/BF00839164

Cheng, X., and Su, H. (2010). Effects of climatic temperature stress on cardiovascular diseases. *Eur. J. Intern. Med.* 21, 164–167. doi: 10.1016/j.ejim.2010.03.001

Couto, M., Stang, J., Horta, L., Stensrud, T., Severo, M., Mowinckel, P., et al. (2015). Two distinct phenotypes of asthma in elite athletes identified by latent class analysis. *J. Asthma* 52, 897–904. doi: 10.3109/02770903.2015.1067321

Daviskas, E., Gonda, I., and Anderson, S. D. (1991). Local airway heat and water vapour losses. *Respir. Physiol.* 84, 115–132. doi: 10.1016/0034-5687(91)90023-C

Deal, E. C., McFadden, E. R., Ingram, R. H., Strauss, R. H., and Jaeger, J. J. (1979). Role of respiratory heat exchange in production of exercise-induced asthma. *J. Appl. Physiol.* 46, 467–475. doi: 10.1152/jappl.1979.46.3.467

Diment, B. C., Fortes, M. B., Edwards, J. P., Hanstock, H. G., Ward, M. D., Dunstall, H. M., et al. (2015). Exercise intensity and duration effects on in vivo immunity. *Med. Sci. Sports Exerc.* 47, 1390–1398. doi: 10.1249/MSS.0000000000000562

Eccles, R. (2002). An explanation for the seasonality of acute upper respiratory tract viral infections. *Acta Otolaryngol.* 122, 183–191. doi: 10.1080/00016480252814207

Eiken, O., Kaiser, P., Holmér, I., and Baer, R. (1989). Physiological effects of a mouth-borne heat exchanger during heavy exercise in a cold environment. *Ergonomics* 32, 645–653. doi: 10.1080/00140138908966139

Eriksson, L. M., Irewall, T., Lindberg, A., and Stenfors, N. (2018). Prevalence, age at onset, and risk factors of self-reported asthma among Swedish adolescent elite cross-country skiers. *Scand. J. Med. Sci. Sport.* 28, 180–186. doi: 10.1111/sms.12879

Eschenbacher, W. L., Moore, T. B., Lorenzen, T. J., Weg, J. G., and Gross, K. B. (1992). Pulmonary responses of asthmatic and normal subjects to different temperature and humidity conditions in an environmental chamber. *Lung An Int. J. Lungs Airways Breath.* 170, 51–62. doi: 10.1007/BF00164755

Federation Internationale de Ski (2018). *The International Ski Competition Rules (ICR) Book II*. Available online at: www.fis-ski.com

Fontanari, P., Burnet, H., Zattara-Hartmann, M. C., and Jammes, Y. (1996). Changes in airway resistance induced by nasal inhalation of cold dry, dry, or moist air in normal individuals. *J. Appl. Physiol.* 81, 1739–1743. doi: 10.1152/jappl.1996.81.4.1739

Fontanari, P., Zattara-Hartmann, M. C., Burnet, H., and Jammes, Y. (1997). Nasal eupnoeic inhalation of cold, dry air increases airway resistance in asthmatic patients. *Eur. Respir. J.* 10, 2250–2254. doi: 10.1183/09031936.97.10102250

Frischhut, C., Kennedy, M. D., Niedermeier, M., and Faulhaber, M. (2020). Effects of a heat and moisture exchanger on respiratory function and symptoms post cold air exercise. *Scand. J. Med. Sci. Sports* 30:591–601. doi: 10.1111/sms.13603

Gilbert, I. A., and McFadden, E. R. (1992). Airway cooling and rewarming. The second reaction sequence in exercise- induced asthma. *J. Clin. Invest.* 90, 699–704. doi: 10.1172/JCI115940

Gravelyn, T. R., Capper, M., and Eschenbacher, W. L. (1987). Effectiveness of a heat and moisture exchanger in preventing hyperpnoea induced bronchoconstriction in subjects with asthma. *Thorax* 42, 877–880. doi: 10.1136/thx.42.11.877

Griffin, M. P., McFadden, E. R., and Ingram, R. H. (1982). Airway cooling in asthmatic and nonasthmatic subjects during nasal and oral breathing. *J. Allergy Clin. Immunol.* 69, 354–359. doi: 10.1016/0091-6749(82)90145-2

Hahn, A., Anderson, S. D., Morton, A. R., Black, J. L., and Fitch, K. D. (1984). A reinterpretation of the effect of temperature and water content of the inspired air in exercise-induced asthma. *Am. Rev. Respir. Dis.* 130, 575–579.

Hampel, R., Breitner, S., Rückerl, R., Frampton, M. W., Koenig, W., Phipps, R. P., et al. (2010). Air temperature and inflammatory and coagulation responses in men with coronary or pulmonary disease during the winter season. *Occup. Environ. Med.* 67, 408–416. doi: 10.1136/oem.2009.048660

Handley, B. A., and Webster, A. J. F. (1995). Some factors affecting the airborne survival of bacteria outdoors. *J. Appl. Bacteriol.* 79, 368–378. doi: 10.1111/j.1365-2672.1995.tb03150.x

Harju, T., Mäkinen, T., Näyhä, S., Laatikainen, T., Jousilahti, P., and Hassi, J. (2010). Cold-related respiratory symptoms in the general population. *Clin. Respir. J.* 4, 176–185. doi: 10.1111/j.1752-699X.2009.00172.x

Heir, T., and Larsen, S. (1995). The influence of training intensity, airway infections and environmental conditions on seasonal variations in bronchial responsiveness in cross-country skiers. *Scand. J. Med. Sci. Sports* 5, 152–159. doi: 10.1111/j.1600-0838.1995.tb00029.x

International Biathlon Union (1998). *6.6 Weather Conditions. IBU Event Compet. Rules 03, 61*. Available online at: https://www.biathlonworld.com/downloads/ (accessed January 25, 2019).

Jackson, A., Hull, J., Hopker, J., Gowers, W., and Dickinson, J. (2018). A heat and moisture exchange mask to reduce exercise induced bronchoconstriction severity. *Euro. Resp. J.* 52(Suppl. 62):PA665. doi: 10.1183/13993003.congress-2018.PA665

Josenhans, W. T., Melville, G. N., and Ulmer, W. T. (2011). The effect of facial cold stimulation on airway conductance in healthy man. *Can. J. Physiol. Pharmacol.* 47, 453–457. doi: 10.1139/y69-080

Karjalainen, E. M., Laitinen, A., Sue-Chu, M., Altraja, A., Bjermer, L., and Laitinen, L. A. (2000). Evidence of airway inflammation and remodeling in ski athletes with and without bronchial hyperresponsiveness to methacholine. *Am. J. Respir. Crit. Care Med.* 161, 2086–2091. doi: 10.1164/ajrccm.161.6.9907025

Kennedy, M. D., Davidson, W. J., Wong, L. E., Traves, S. L., Leigh, R., and Eves, N. D. (2016). Airway inflammation, cough and athlete quality of life in elite female cross-country skiers: a longitudinal study. *Scand. J. Med. Sci. Sport*, 26, 835–842. doi: 10.1111/sms.12527

Kennedy, M. D., and Faulhaber, M. (2018). Respiratory function and symptoms post cold air exercise in female high and low ventilation sport athletes. *Allergy, Asthma Immunol. Res.* 10, 43–51. doi: 10.4168/aair.2018.10.1.43

Kennedy, M. D., Steele, A. R., Parent, E. C., and Steinback, C. D. (2019). Cold air exercise screening for exercise induced bronchoconstriction in cold weather athletes. *Respir. Physiol. Neurobiol.* 269:103262. doi: 10.1016/j.resp.2019.103262

Kippelen, P., Anderson, S. D., and Hallstrand, T. S. (2018). Mechanisms and biomarkers of exercise-induced bronchoconstriction. *Immunol. Allergy Clin. North Am.* 38, 165–182. doi: 10.1016/j.iac.2018.01.008

Kippelen, P., Fitch, K. D., Anderson, S. D., Bougault, V., Boulet, L.-P., Rundell, K. W., et al. (2012). Respiratory health of elite athletes - preventing airway injury: a critical review. *Br. J. Sports Med.* 46, 471–476. doi: 10.1136/bjsports-2012-091056

Koskela, H., Pihlajamäki, J., Pekkarinen, H., and Tukiainen, H. (1998). Effect of cold air on exercise capacity in COPD: Increase or decrease? *Chest* 113, 1560–1565. doi: 10.1378/chest.113.6.1560

Koskela, H., and Tukiainen, H. (1995). Facial cooling, but not nasal breathing of cold air, induces bronchoconstriction: A study in asthmatic and healthy subjects. *Eur. Respir. J.* 8, 2088–2093. doi: 10.1183/09031936.95.08122088

Koskela, H., Tukiainen, H., Kononoff, A., and Pekkarinen, H. (1994). Effect of whole-body exposure to cold and wind on lung function in asthmatic patients. *Chest* 105, 1728–1731. doi: 10.1378/chest.105.6.1728

Koskela, H. O., Koskela, A. K., and Tukiainen, H. O. (1996). Bronchoconstriction due to cold weather in COPD: the roles of direct airway effects and cutaneous reflex mechanisms. *Chest* 110, 632–636. doi: 10.1378/chest.110.3.632

Kurowski, M., Jurczyk, J., Moskwa, S., Jarzebska, M., Krysztofiak, H., and Kowalski, M. L. (2018a). Winter ambient training conditions are associated with increased bronchial hyperreactivity and with shifts in serum innate immunity proteins in young competitive speed skaters. *Arch. Med. Sci.* 14, 60–68. doi: 10.5114/aoms.2017.69438

Kurowski, M., Jurczyk, J., Olszewska-Ziaber, A., Jarzebska, M., Krysztofiak, H., and Kowalski, M. L. (2018b). A similar pro/anti-inflammatory cytokine balance is present in the airways of competitive athletes and non-exercising asthmatics. *Adv. Med. Sci.* 63, 79–86. doi: 10.1016/j.advms.2017.07.004

Larsen, J. N., and Fondahl, G. (eds.) (2015). *Arctic Human Development Report: Regional Processes and Global Linkages*. Copenhagen: Nordisk Ministerråd.

Larsson, K., Tornling, G., Gavhed, D., Müller-Suur, C., and Palmberg, L. (1998). Inhalation of cold air increases the number of inflammatory cells in the lungs in healthy subjects. *Eur. Respir. J.* 12, 825–830. doi: 10.1183/09031936.98.12040825

Larsson, L., Hemminqsson, P., and Boethius, G. (1994). Self-reported obstructive airway symptoms are common in young cross-country skiers. *Scand. J. Med. Sci. Sports* 4, 124–127. doi: 10.1111/j.1600-0838.1994.tb00414.x

Lereim, I. (2007). *Sport at Low Temperature: Prevention of Cold Injuries in Snow Sports.* FIS Medical Committee Education Series, 9.

Mäkinen, T. M., Juvonen, R., Jokelainen, J., Harju, T. H., Peitso, A., Bloigu, A., et al. (2009). Cold temperature and low humidity are associated with increased occurrence of respiratory tract infections. *Respir. Med.* 103, 456–462. doi: 10.1016/j.rmed.2008.09.011

McFadden, E. J., Pichurko, B., Bowman, H., Ingentio, E., Burns, S., Dowling, N., et al. (1985). Thermal mapping of the airways in humans. *J. Appl. Physiol.* 58, 564–570. doi: 10.1152/jappl.1985.58.2.564

Millqvist, E., Bake, B., Bengtsson, U., and Löwhagen, O. (1995). A breathing filter exchanging heat and moisture prevents asthma induced by cold air. *Allergy* 50, 225–228. doi: 10.1111/j.1398-9995.1995.tb01138.x

Millqvist, E., Bengtsson, U., and Bake, B. (1987). Occurrence of breathing problems induced by cold climate in asthmatics–a questionnaire survey. *Eur. J. Respir. Dis.* 71, 444–9.

Millqvist, E., Bengtsson, U., and Löwhagen, O. (2000). Combining a β2-agonist with a face mask to prevent exercise-induced bronchoconstriction. *Allergy Eur. J. Allergy Clin. Immunol.* 55, 672–675. doi: 10.1034/j.1398-9995.2000.00558.x

Näyhä, S., Hassi, J., Jousilahti, P., Laatikainen, T., and Ikäheimo, T. M. (2011). Cold-related symptoms among the healthy and sick of the general population: National FINRISK Study data, 2002. *Public Health* 125, 380–388. doi: 10.1016/j.puhe.2011.02.014

Niinimaa, V., Cole, P., Mintz, S., and Shephard, R. J. (1980). The switching point from nasal to oronasal breathing. *Respir. Physiol.* 42, 61–71. doi: 10.1016/0034-5687(80)90104-8

Nisar, M., Spence, D. P. S., West, D., Haycock, J., Jones, Y., Walshaw, M. J., et al. (1992). A mask to modify inspired air temperature and humidity and its effect on exercise induced asthma. *Thorax* 47, 446–450. doi: 10.1136/thx.47.6.446

Noback, M. L., Harvati, K., and Spoor, F. (2011). Climate-related variation of the human nasal cavity. *Am. J. Phys. Anthropol.* 145, 599–614. doi: 10.1002/ajpa.21523

Norqvist, J., Eriksson, L., Söderström, L., Lindberg, A., and Stenfors, N. (2015). Self-reported physician-diagnosed asthma among Swedish adolescent, adult and former elite endurance athletes. *J. Asthma* 52, 1046–1053. doi: 10.3109/02770903.2015.1038389

Pekkarinen, H., Tukiainen, H., Litmanen, H., Huttunen, J., Karstu, T., and Länsimies, E. (1989). Effect of submaximal exercise at low temperatures on pulmonary function in healthy young men. *Eur. J. Appl. Physiol. Occup. Physiol.* 58, 821–825. doi: 10.1007/BF02332213

Rasi, H., Kuivila, H., Pölkki, T., Bloigu, R., Rintamäki, H., and Tourula, M. (2017). A descriptive quantitative study of 7- and 8-year-old children's outdoor recreation, cold exposure and symptoms in winter in Northern Finland. *Int. J. Circumpolar Health* 76:1298883. doi: 10.1080/22423982.2017.1298883

Rindert, B. (1993). *Termodynamik, Hydrostatik Och Molnfysik*. Uppsala: Uppsala Universitet.

Rocklöv, J., and Forsberg, B. (2008). The effect of temperature on mortality in Stockholm 1998-2003: a study of lag structures and heatwave effects. *Scand. J. Public Heal.* 36, 516–523. doi: 10.1177/1403494807088458

Rundell, K. W., Im, J., Mayers, L. B., Wilber, R. L., Szmedra, L., and Schmitz, H. R. (2001). Self-reported symptoms and exercise-induced asthma in the elite athlete. *Med. Sci. Sports Exerc.* 33, 208–213. doi: 10.1097/00005768-200102000-00006

Sandsund, M., Saursaunet, V., Wiggen, O., Renberg, J., Farevik, H., and Van Beekvelt, M. C. P. (2012). Effect of ambient temperature on endurance performance while wearing cross-country skiing clothing. *Eur. J. Appl. Physiol.* 112, 3939–3947. doi: 10.1007/s00421-012-2373-1

Scott, E. E. F., Hamilton, D. F., Wallace, R. J., Muir, A. Y., and Simpson, A. H. R. W. (2016). Increased risk of muscle tears below physiological temperature ranges. *Bone Jt. Res.* 5, 61–65. doi: 10.1302/2046-3758.52.2000484

Seifert, J. G., Frost, J., and St Cyr, J. A. (2017). Recovery benefits of using a heat and moisture exchange mask during sprint exercise in cold temperatures. *SAGE Open Med.* 5:205031211774098. doi: 10.1177/2050312117740985

Sjöström, R., Söderström, L., Klockmo, C., Patrician, A., Sandström, T., Björklund, G., et al. (2019). Qualitative identification and characterisation of self-reported symptoms arising in humans during experimental exposure to cold air. *Int. J. Circumpolar Health* 78:1583528. doi: 10.1080/22423982.2019.1583528

Spence, L., Brown, W. J., Pyne, D. B., Nissen, M. D., Sloots, T. P., McCormack, J. G., et al. (2007). Incidence, etiology, and symptomatology of upper respiratory illness in elite athletes. *Med. Sci. Sports Exerc.* 39, 577–586. doi: 10.1249/mss.0b013e31802e851a

Stensrud, T., Berntsen, S., and Carlsen, K. H. (2007). Exercise capacity and exercise-induced bronchoconstriction (EIB) in a cold environment. *Respir. Med.* 101, 1529–1536. doi: 10.1016/j.rmed.2006.12.011

Stickland, M. K., Rowe, B. H., Spooner, C. H., Vandermeer, B., and Dryden, D. M. (2012). Effect of warm-up exercise on exercise-induced bronchoconstriction. *Med. Sci. Sports Exerc.* 44, 383–391. doi: 10.1249/MSS.0b013e31822fb73a

Strauss, R. H., McFadden, E. R., Ingram, R. H., Jaeger, J. J., and Stearns, D. R. (1977). Enhancement of Exercise-Induced Asthma by Cold Air. *N. Engl. J. Med.* 297, 743–747. doi: 10.1056/NEJM197710062971402

Sue-Chu, M. (2012). Winter sports athletes: Long-term effects of cold air exposure. *Br. J. Sports Med.* 46, 397–401. doi: 10.1136/bjsports-2011-090822

Sue-Chu, M., Karjalainen, E. M., Altraja, A., Laitinen, A., Laitinen, L. A., Næss, A. B., et al. (1998). Lymphoid aggregates in endobronchial biopsies from young elite cross- country skiers. *Am. J. Respir. Crit. Care Med.* 158, 597–601. doi: 10.1164/ajrccm.158.2.9711012

Sue-Chu, M., Larsson, L., Moen, T., Rennard, S. I., and Bjermer, L. (1999). Bronchoscopy and bronchoalveolar lavage findings in cross-country skiers with and without "ski asthma." *Eur. Respir. J.* 13, 626–632. doi: 10.1183/09031936.99.13362699

Svendsen, I. S., Taylor, I. M., Tønnessen, E., Bahr, R., and Gleeson, M. (2016). Training-related and competition-related risk factors for respiratory tract and gastrointestinal infections in elite cross-country skiers. *Br. J. Sports Med* 50, 809–815. doi: 10.1136/bjsports-2015-095398

Therminarias, A., Oddou, M. F., Favre-Juvin, A., Flore, P., and Delaire, M. (1998). Bronchial obstruction and exhaled nitric oxide response during exercise in cold air. *Eur. Respir. J.* 12, 1040–1045. doi: 10.1183/09031936.98.12051040

Valtonen, M., Waris, M., Vuorinen, T., Eerola, E., Hakanen, A. J., Mjosund, K., et al. (2019). Common cold in Team Finland during 2018 Winter Olympic Games (PyeongChang): epidemiology, diagnosis including molecular point-of-care testing (POCT) and treatment. *Br. J. Sports Med.* 53, 1093–1098. doi: 10.1136/bjsports-2018-100487

Verma, M., Seto-Poon, M., Wheatley, J. R., Amis, T. C., and Kirkness, J. P. (2006). Influence of breathing route on upper airway lining liquid surface tension in humans. *J. Physiol.* 574, 859–866. doi: 10.1113/jphysiol.2005.102129

Wennergren, G., Ekerljung, L., Alm, B., Eriksson, J., Lötvall, J., and Lundbäck, B. (2010). Asthma in late adolescence–farm childhood is protective and the prevalence increase has levelled off. *Pediatr Allergy Immunol* 21, 806–813. doi: 10.1111/j.1399-3038.2010.01057.x

Wiggen, O. N., Heidelberg, C. T., Waagaard, S. H., Færevik, H., and Sandbakk, O. (2016). The effects of cold environments on double-poling performance and economy in male cross-country skiers wearing a standard racing suit. *Int. J. Sports Physiol. Perform.* 11, 776–782. doi: 10.1123/ijspp.2015-0232

Zawadski, D. K., Lenner, K. A., and McFadden, E. R. (1988). Comparison of intraairway temperatures in normal and asthmatic subjects after hyperpnea with hot, cold, and ambient air. *Am. Rev. Respir. Dis.* 138, 1553–1558. doi: 10.1164/ajrccm/138.6.1553

Conflict of Interest: In May 2019 the authors were provided with 4 complimentary HMEs with disposable filters for use in forthcoming research by Vapro Produktutveckling AB, Västerås, Sweden.

frontiers in Sports and Active Living

ORIGINAL RESEARCH
published: 28 April 2020
doi: 10.3389/fspor.2020.00032

Self-Reported Physical Activity, Injury, and Illness in Canadian Adolescent Ski Racers

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Youth ski racers spend a considerable amount of time on snow and this may detract from other activities known to influence fundamental movement skills and overall health related outcomes. Parents of racers (n = 52 F; n = 44 M; age range 9–14 years) registered in the Canadian club system completed a baseline medical questionnaire during preseason testing in 2017. We describe physical activity volume and sport participation outside of physical education classes over the previous 12 months and report on injuries, medication use and health care utilization. The mean number of activities participated was five (range 1–14) with cycling, hiking, and swimming as the preferred choice and a cumulative mean of just under 400 h of activity was reported (range F 27–1,015; M 62–869 h/year) in the past year. During the past 12 months 16% of the athletes reported being injured and injury severity impacted return to sport with range of reported days missed from 1 to 365 days. Thirteen non-concussive injuries were reported in alpine skiing and females (12%, 6/52) reported more lower limb injuries than males (7%, 3/44). More males were concussed over their lifetime, with alpine skiing accounting for 46% and mountain biking 15%. Most athletes (85%) did not take medication on a regular basis and those that did had a medical diagnosis. The frequency of respiratory conditions was 13% (12/96) with males reporting slightly more cases than females. No difference in emergency visits occurred (25%) between males and females in the past 12 months, however females reported more (n = 102) allied health care, sport medicine and x-rays appointments when compared to males (n = 65). In summary, a high volume of physical activity (an hour plus per day) over the previous 12 months was reported with racers participating in several activities outside of skiing, likely honing their fundamental movement skills. Close proximity to the mountains may have influenced their choices of activity outside of ski racing, and their injuries and a variety of health conditions were typical of their age group. Future research employing wearable technology to objectively quantify the volume and intensity of physical activity participation is recommended.

Keywords: adolescents, ski racers, physical activity participation, injury, hospital visits

OPEN ACCESS

Edited by:
Jörg Spörri,
Balgrist University Hospital, Switzerland

Reviewed by:
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Specialty section:
This article was submitted to Sports Science, Technology and Engineering,
a section of the journal Frontiers in Sports and Active Living

Received: *22 October 2019*
Accepted: *17 March 2020*
Published: *28 April 2020*

Citation:
Doyle-Baker PK and Emery CA (2020) Self-Reported Physical Activity, Injury, and Illness in Canadian Adolescent Ski Racers. Front. Sports Act. Living 2:32. doi: 10.3389/fspor.2020.00032

INTRODUCTION

Alpine ski racers as young as 10–14 years spend a considerable amount of time on snow during the ski season. This may detract from other activities known to influence fundamental movement skills (FMS) and overall health related outcomes. The Canadian Alpine Long-term Athlete Development model (LTAD) was recently redesigned in 2019 with the emphasis toward a more staged development so as to help younger ages achieve both athlete success and continued life-long participation in the sport (https://ltad.alpinecanada.org). The Training and Competition Volume Matrix within the LTAD identifies volumes and quantities associated with performance programs, however it does not address the volume of physical activity (PA) outside the ski training paradigm. Inclusion of all PA and other sports young ski racers participate in should be considered since this added exposure may contribute positively or negatively to their health and performance.

A review of the literature supports that FMS are associated with PA participation (Williams et al., 2008), however, failure to develop these skills during childhood may impact a child's future physical activity level in adulthood (Lloyd et al., 2014; Henrique et al., 2016; Jaakkola et al., 2016). While these studies focus on the relationship between FMS and PA participation, only a few others have gone beyond and identified health indicators (Tremblay et al., 2016; Canadian Physical Activity Guidelines, 2018). Yet, an underlying belief exists that most health indicator benefits occur through PA and sport participation in youth.

Typical health indicators, such as waist circumference, body weight and body mass index (BMI), have been associated positively with FMS (Lubans et al., 2010; Robinson et al., 2015; Duncan et al., 2016; O'Brien et al., 2016) and with sport participation although the direction of the relationship is not clear (Cairney and Veldhuizen, 2017; Comeau et al., 2017). Ski racers for example tend to be heavier than age matched non-athletes, as larger anthropometric characteristics are advantageous in alpine ski racing (Raschner et al., 1995). However, in terms of both physical and mental health indicators other than those related to body composition, not much information is available in the 10–14 year-old ski racing group.

Recently Müller et al. (2017a,b), published a study that examined the incidence, prevalence, and severity of traumatic and overuse injuries and illnesses of elite youth ski racers, 15 years and under. The authors reported a relatively low injury incidence (traumatic, IR = 0.86/1,000 h of training; overuse, IR = 0.28/1,000 h) and high annual illness prevalence (2.4/athlete) in youth ski racers. In addition to this, the knee was the most commonly affected body part (traumatic knee injuries 36.5%), a high annual prevalence of overuse injuries (82%) and prevalence of bone fractures was high (46%) and 66% of the illnesses reported were respiratory tract infections. Overuse injuries and respiratory diseases, although not traditionally thought of as health indicators certainly influence an adolescent's health.

Reliable data collection through injury and illness surveillance methods in youth alpine ski racers remains a challenge (Spörri et al., 2017). In Canada, the independent operation of ski clubs leads to significant difficulties for injury and illness surveillance. The Public Health Agency of Canada reported that alpine skiing is the third-leading cause after hockey and snowboarding for emergency departments visit in children. Furthermore, skiing (12.6%) had the highest rate of hospitalization when compared to snowboarding (11.3%) and hockey (3.6%) (Warda and Yanchar, 2012).

Head injuries, although thought to be less common are noteworthy, since a child's brain is still developing and a brain injury such as a concussion, impacts them with a range of negative consequences, including headaches, depression, memory problems and poor school performance. Increased concussion recognition has many athletes seeking a diagnosis and as such emergency department visits for sport-related concussions doubled in children from 1997 to 2007 (Bakhos et al., 2010). In a recent study of elite youth ski racers, 28.8% of the injuries reported (19/66) were related to the head and 84% (16/19) of these were concussions during the 2016/2017 ski season (Anderson et al., 2019).

Recently, developmental disorders with similar symptomology as listed above for concussions have been associated with increased injury proneness (Nelson et al., 2016). Given that concussions are emerging as an issue in alpine skiing, where cumulative impacts to the head is not uncommon, more research is needed to rule out the possibility of the interactive effects of this combination. According to Pol et al. (2019) a better understanding of how sport injuries occur is warranted with consideration toward adopting a larger health focus so as to improve prevention for medical, economic, scientific and sports success reasons.

The primary aim of this study was to describe the participation of all sport and physical activity by type and volume, and the secondary aim was to provide insight into the injuries reported and health indicators (health care utilization, illness, medication use) in adolescent youth ski club racers in Western Canada.

METHODS

Participants and Design

Alberta Alpine Ski Association (AASA) is the provincial governing body for alpine ski-racing, and guides standards for programs for over 4,800 athletes, coaches, officials, and volunteers throughout the province of Alberta in Canada (http://albertaalpine.ca/). Within the AASA are numerous ski-clubs, that are privately managed through parent volunteers and/or respective coach hires. Athletes from 5 ski clubs registered in the AASA in the under 12 and 14 (U12, U14) age group categories participated in this study. Participating skiers had been previously recruited for a pre-experimental study during the 2017 pre-season dryland training period on balance agility, and strength exercises (BASE) that required a sample size of $n = 93$ to achieve 80% power at an alpha level of 0.05 (Doyle-Baker et al., 2017). A baseline medical questionnaire was included in the package with other study forms and sent home to the parents prior to dryland fitness testing. The self-report questionnaire included a mixture of question types (single and multiple response, rating scales, true/false statements and open-ended) and required 10–15 min to complete and most parents did so at home. A total of 96 questionnaires were returned ($n = 52$ F; $n = 44$ M), with 4 forms that had incomplete sections.

Ethics Statement

Athletes and parents were informed of the study aims, requirements, and risks before providing written and verbal participant assent, and written parental consent. The study was performed according to the Declaration of Helsinki. The research was approved by the Conjoint Health Research Ethics Board of the University of Calgary (REB:16-1818).

Questionnaire Details

The baseline medical questionnaire was developed from an injury surveillance system adapted for high school basketball from the Canadian Intercollegiate Sports Injury Registry (CISIR) (Emery et al., 2007). The questionnaire has been previously used in other studies as a baseline for sport and recreation participation and injury at the University of Calgary in Alberta (Richmond et al., 2016). In this current study we were interested in identifying all other activities ski racers participated in, past injury and injury types from all activities, past diagnosis related to various conditions (bone fracture, systemic diseases, respiratory, circulation or heart, neurological disorder, headaches), medication and supplement use, and health care utilization (practitioner and hospital visits).

The questionnaire asked for detailed information on frequency, hours, and number of weeks of participation across 38 activities, not including physical education (PE) class, over three time periods. The first time period was related to the 6 weeks prior to the start of the preseason dryland training program, the second was related to the past year, i.e., previous 12 months, which matches the time frame from the Canadian General Social Survey, and the third didn't specify a time duration and was considered to be over a lifetime. Within the questionnaire, injury history was based on date, activity, type, body part, treatment and return to sport (RTS) and was divided into concussion (defined as either diagnosed or not or been "knocked out" or had their "bell rung"), non-concussive injury (defined as requiring medical attention or at least 1 day of missed participation in the past 12 months), and any injury not completely healed.

The data was de-identified and entered into REDCap, a secure web-based application by research assistants and the PI cleaned and checked the data (Harris et al., 2009). Where necessary the paper copy of the questionnaire was reviewed, and/or phone call follow up check with the parents occurred.

Statistical Analysis

Appropriate measures of central tendency are reported [means and 99% confidence intervals (99% CI)] for participant characteristics from the BASE study by sex: age, height, weight, WC, BMI and Predicted VO_{2max}. A crude analysis was carried out to assess the distribution of raw data using the Kolmogorov-Smirnov test, which demonstrated all data to have a normal distribution ($p > 0.05$). The majority of the PA and health variables are described as rates, means, [standard deviations (±)] or frequencies (%). Data was analyzed using IBM SPSS 24 software and STATA V.15.

RESULTS

Ski racing uses the 1st of January as the birth month for the yearly cut-off date for grouping the various competition categories. This relative age effect (RAE) is present in all age categories at both national, as well as at international levels in skiing (Müller et al., 2015). However, in this study the chronological age was calculated based on the cut-off date for collecting the questionnaires.

Participant Characteristics

A total of 96 racers (M = 44; F = 52) born between 2004 and 2008 (2004 $n = 20$; 2005 $n = 20$; 2006 $n = 27$; 2007 $n = 28$; 2008 $n = 1$) completed the self-report questionnaire. Mean age as of the 25th of September 2017 was 11.5 ± 1.1 (range 9.3–13.7 years) and there was no statistical difference across the mean age of the five clubs (11.4 $n = 38$; 12.0 $n = 4$; 12.3 $n = 13$; 11.2 $n = 19$; 11.3 $n = 22$). The anthropometric characteristics of the racers during the pre-season testing are described in **Table 1**. The biological maturity status was not accounted for, however just 17.3% of the females (9/52) self-reported a regular menstrual cycle with 10 or more monthly periods per year and a mean onset of 12.0 ± 0.8 years. This age of menarche follows within the estimated mean range of 12–13 years in Canada (Al-Sahab et al., 2010).

Six levels of parental educational attainment were included in the questionnaire (junior high or less, high school, technical, undergrad, graduate or post graduate degree). The majority of the racers came from families where both parents (parent 1; $n = 93$; parent 2, $n = 86$) had a level 4 educational attainment (36.5%, $n = 35$; 27.1%, $n = 26$) or level 5 and 6 (above 39.7%, $n = 37$; 46.9%, $n = 45$) respectively.

Physical and Activity Participation

The questionnaire was designed to capture hours of physical activity participation and categories of recreational activity. The 38 recreational activities were listed alphabetically in the questionnaire and included: Aerobics, Alpine skiing, Badminton, Baseball, Basketball, Boxing (incl. kick), Cross-country skiing, Cycling (road or mtn.), Dance, Dirt biking, Diving, Field hockey, Figure skating, Floor hockey, Football,

TABLE 1 | Anthropometric characteristics separated by sex ($N = 96$).

	(Mean, 95% CI)	
Characteristic	**F $n = 52$**	**M $n = 44$**
Age (yr.)	11.7 (10.5, 12.9)	11.9 (10.5, 12.9)
Height (cm)	151.5 (138.4, 160.5)	150.7 (137.1, 164.4)
Weight (kg)	41.7 (30.3, 49.6)	39.3 (27.4, 51.1)
WC (cm)	66.1 (58.8, 72.0)	65.3 (59.5, 74.1)
BMI (kg/m^2)	18.1 (15.1, 20.3)	17.1 (14.6, 19.6)
PredictVO_{2max} (ml/kg/min^{-1})	49.2 (45.8, 52.5)	50.2 (45.0, 55.4)

yr., year; cm, centimeters; kg, kilograms; kg/m^2, kilograms per meters squared; VO_2 max, maximal oxygen uptake; ml/kg/min^{-1}, milliliters per kilogram per minute; 99% CI, 99% confidence interval.

Golf, Gymnastics, Hiking/Scrambling, Hockey, Horse riding, Lacrosse, Martial arts, Rock climbing, Rollerblading, Rugby, Running, Skate/long boarding, Snowboarding, Soccer, Squash, Speed skating, Swimming, Tennis, Track and field, Volleyball, Water polo, Weight training, Wrestling, with an additional open ended category of "Other." Other sports recorded by the parents included: Climbing, Dryland Training, Kayaking, Pickleball/Parkour, Summer Camp, Water Skiing, Yoga, and not specified.

Past 6 Weeks of Sport and PA Participation Hours Outside of PE Class

In the 6 weeks prior to the start of pre-season training (4 weeks of August and first 2 weeks of September), 95% of the athletes (91/96) participated in sport or recreational activity outside of their PE class. Three males and 1 female reported that they did not, and one was blank. The majority (63.5%, 61/96) participated in 2–5 activities with a mean of 4.2 ± 2.4 (range 1–15) during this period. The most popular activities, regardless of sex, were cycling-road/mtn (77%), swimming (53%) and hiking/scrambling (45%) (see **Table 2**).

A range of hours per activity per week from 30 min to 56 h was reported. Only a handful of questionnaires had the level of intensity per activity session per week completed and when recorded the ranges included 1–10 mild, 2–7 moderate, and 1-vigorous.

Athletes who attended dedicated camps during the month of August recorded large volumes of daily activity during a week. These camps included: 1 week on site at the YMCA Camp Chief Hector (56 h), swimming (12–21 h), cycling (15–20 h), gymnastics (16 h), alpine skiing (13–15 h), volleyball (15 h), and golf (15 h). Not all activities from the list of 38 were participated in. This may be related to factors such as a lack of summer time offerings, proximity to location and interest in these activities (boxing including kick, ice hockey, snowboarding, speed skating and water polo).

TABLE 2 | Athlete participation in sport and activity during the past 12 months.

Activity over past 12 months	$N = 96$	%
Alpine Ski Racing	96	100
Cycling (road/mtn)	55	57.3
Swimming	48	50.0
Hiking/Scrambling	35	36.4
Running	31	32.3
Soccer	24	25.0
Golf, Horseback riding, Rock climbing	16	16.7
Basketball,	12	12.5
Volleyball, Weight training	10	10.4
Gymnastics, Roller Blading	8	8.3
Badminton, Baseball, Dance, Skateboard, Track and Field	7	7.3
Marital arts	6	6.3
Floor hockey, Tennis	5	5.2
Aerobics, Diving, Figure Skating, Rugby	4	4.2
Cross-country skiing, Dirt Biking, Lacrosse, Squash, Wrestling,	2	2.0
Football and Other	1	1.0
Boxing (incl. kick), ice hockey, field hockey, snowboarding, speed skating, water polo	0	0.0

Past 12 Months of Sport and PA Participation Hours Outside of PE Classes

In the 12 months prior to the start of the 2017 preseason training, 96% of the racers ($n = 92/96$) participated in sport or recreational activity outside of their PE classes (see **Table 2**). One male reported they did not, and three females left the section blank. The mean number of sports participated in with the inclusion of alpine skiing during the past 12 months was 5 (4.9 ± 2.8) and the number per athlete ranged from 1 to 14.

The cumulative total hours over the past 12 months were calculated from the hours per week multiplied by the number of weeks the athlete participated in the activity. There was no difference in PA participation between the male and female mean total hours reported (M 44, 389 ± 239; F 52, 398 ± 241), but the range was wider in the females (M 62–869; F 27–1,015 h) respectively, over the past 12 months.

Alpine Skiing Sport Participation Hours

The mean total hours reported over the past 12 months for alpine skiing in 91 athletes was 264.21 ± 170.2 (range 12–725). There were 12 athletes who reported over 480 h and 3 females had over 650 h. Both females and males on average completed 20 weeks of ski training (20.7 ± 7.69) with a range of 1–36 weeks, however the number of hours per week varied depending on the program category enrolled in. Racers select from 1 to 3 days per week of ski training with different combinations such as 3 full days which included both weekend days, or 2 full weekend days and a few hours one evening, or both weekend days, or only 1 day per weekend. The mean number of weekly hours was 13.43 ± 4.92 (range of 3–25), with females reporting slightly more (14.21 ± 4.73; range of 5–36) then the males (13.32 ± 5.36; range 3–24) hours. Some athletes participated in over 16 h per week of ski training.

Injuries Were Reported by Activity Over a Lifetime and Over the Past 12 Months

Concussion

The number of concussions reported over a lifetime was 13 (13.5%; 3/96) and in the past 12 months was 4 (4.3%; 4/96). Males reported a higher prevalence of concussions (9/13) when compared to females (4/13). Alpine skiing had the highest prevalence of concussions (46.1%; 6/13) followed by mountain biking (15.4%; 2/13) over a lifetime. No memory loss or dizziness was reported however, those that did lose consciousness did so within the range of 3–10 s. On average, the number of days before return to sport was 14 (13.7 ± 6.5) with a range of 7–28 days. The majority of concussions were diagnosed by a physician (69.2%; 9/13) and two females (15.3%) reported they suffered from headaches post-concussion (see **Table 3**). Only one athlete reported having two concussion (F) over a lifetime, both related to playing tag during dryland training (2014).

TABLE 3 | Reported concussions over a lifetime by sex separated by year, activity, return to sport and diagnosis ($n = 13$).

Sex	Year	Activity	Unconscious seconds	RTS days	Physician DX	Headaches
M	2017	Mountain biking		7	n	
M	2017	Mountain Biking		14	y	
M	2017	Alpine skiing		7	y	
M	2016	Scooter	5	14	y	
M	2016	Alpine Skiing	Not reported	14	n	
M	2016	Alpine Skiing	10	24.5	y	
M	2014	Alpine Skiing	3	7	n	
M	2014	Hockey		14	y	
M	2013	Not reported		14	y	
F	2017	Alpine Skiing		28	y	y
F	2014	Tag		14	y	y
F	2014	Tag		7	y	
F	NR	Alpine Skiing		14	n	

RTS, Return to Sport; DX, Diagnosed; NR, Not reported; No memory loss or dizziness reported.

TABLE 4 | Female non-concussive injury by year separated by body part and type and activity ($n = 13$).

Date	Body part	Injury type	Activity	Treatment description	RTS days
2017-01-15	Wrist	Sprain	Alpine Skiing	Physio	21
2017-02-01	Ankle	Sprain	Alpine Skiing	Rest, physio	4
2017-02-01	Knee	Strain	Cross-country skiing	Physio, ice, pain meds	7
2017-02-10	Knee	Sprain	Alpine Skiing	NR	60
2017-03-01	Ankle	Sprain	Gym Class	Physio, heat/ice	42
2017-03-03	Knee	Tweak [sprain]	Alpine Skiing	Physio	14
2017-03-10	Knee	Sprain	Alpine Skiing	Ice, pain meds	N/R
2017-05-01	Ankle	Sprain	Climbing	Ice	7
2017-07-01	Big toe	Fracture	Walking	Rest	20
2017-07-04	Wrist	Fracture	Walking-fell	Cast, brace	14
2017-07-27	Mouth	Teeth	Baseball	Surgery/ Stitches, ice	15
2016-11-16	Knee	MCL Sprain	Alpine Skiing	Physio	42
2016-10-06	Wrist	Fracture	Bouncy Castle	Cast	12

RTS, Return to Sport; NR, Not reported; Physio, Physiotherapy.

Non-concussive Injuries Reported by Activity

The number of non-concussive injuries reported over a lifetime was 21.8% (21/96) and in the past 12 months was 16.6% (16/96) (**Tables 4**, **5**). The return to sport range was 1–365 and this was influenced by two male athletes who required substantially more days to recovery from fractures in their lower leg (112, 365 days, respectively). As well, three injuries (back sprain, dental surgery and painful ankle) were reported as continuing to be problematic after resuming activities.

Twelve non-concussive injuries over a lifetime (12.5%; F = 7, M = 6) were directly related to alpine skiing and the majority were related to lower leg injuries (F 9.6%, 5/52; M 9.1% 4/44 respectively). Females reported 11 (21.1%; 11/52) non-concussive injuries in the past 12 months and five were from alpine skiing compared to males who reported five (11.3%; 5/44) in the past 12 months with three related to alpine skiing. Only one athlete reported having two injuries (F), both related to walking in the same year (2017).

Physician Diagnosis of Previous Fracture, Arthritis, or Muscle Bone Condition

In addition to the above injuries, 15 fractures were reported with no information related to the activity: 10 in females (2015, growth plate in thumb and fibula; 2013 clavicle and left ankle, 2011 elbow and wrist; no date ankle and wrist) and 5 in males (2017 open growth plates, 2015 knee, 2014 arm and wrist). Therefore, the total number of injuries inclusive of the above (previous fracture 15, concussion 13 and non-concussive injuries 21) reported over a lifetime may be as high a 51.0%, (49/96).

Medical History Related Medication and Supplements Use

The majority of the athletes (85.4%, 82/96) did not take medication on a regular basis and those that did (14.5%, 14/96) reported a medical and or health care professional diagnosis that included cognitive disorders, depression, and reactive airways and asthma (see **Table 6**). Male athletes (18.1%; 8/44) had a greater number of reported attention (ADHD, ADD, or combined; Dyslexia spectrum, Dyslexia and Dysgraphia) or learning issues (coded or anxiety, slow working memory or processing) when compared to females (11.5%; 6/52). The overall frequency of a diagnosed respiratory condition was 12.5% (12/96) with males (13.6%, 6/44) reporting slightly more cases than females (11.5%, 6/52). Only one athlete was diagnosed in 2017, the other cases were reported as occurring between 2007 and 2014 and were no longer considered active conditions.

In total, 53.1 % (51/96) of the athletes reported taking a supplement, of which most were vitamins and minerals (see **Table 7**). More females (59%; 31/52) took supplements when compared to the males (45.4%; 20/44).

TABLE 5 | Males non-concussive injury by year separated by body part, type and activity ($n = 8$).

Date	Body part	Injury type	Activity	Treatment description	RTS days
2017-01-01	Neck	Sprain	Alpine Skiing	Physio	7
2017-04-07	Tibia	Fracture	Alpine Skiing	Cast, Physio	112
2017-08-15	Leg	Fracture	Alpine Skiing	Physio	365
2017-08-15	Back	Sprain	Trampoline	Physio	1
2017-08-25	Foot	Pain	Jumping off swing	NR	NR
2016-12-30	Shoulder	Sprain/ Bruise	Alpine Skiing	Ice	2
2016-12-27	Knee	Strain	Alpine Skiing	Physio, Ice, pain meds	48
2016-03-06	Shin	Deep cut	Alpine Skiing	Stitches	21

RTS, Return to Sport; NR, Not reported; Physio, Physiotherapy.

TABLE 6 | Medical History Diagnosis ($n = 20$) and medication use ($n = 14$) over a lifetime.

Diagnosis	Medications reported
ADHD (4), ADD (1)	Colchicine (1), Concerta (3), Vyvanse (1)
Learning Disorder (1)	Amitriptyline (1)
ADHD (1), Dyslexia spectrum (1), Dyslexia and Dysgraphia (1), Learning disability with dysgraphia (1)	NR
Depression (2)	Amitriptyline (1), Vyvanse (1), NR (1)
Diabetes (1)	Insulin
Asthma (4), Allergy (1)	Ventolin (2), Alvesco (1), NR (2)
NR (2)	Advil (1)

ADHD, Attention deficit hyperactivity disorder; NR, not reported; ADD, Attention deficit disorder.

Health Care Utilization of Practitioner and Services

In the past 12 months 25% of the males (11/44) went to emergency for a variety of reasons including but not limited to a bruised shoulder, a fall, kidney issue, lip surgery, stomach pain, and tibia fracture. Females (25%, 13/52) went to emergency for similar reasons (asthma, concussion, face injury, headache (2), knee injury (3), pneumonia, stomach pain, and wrist fracture), however no females were admitted for an overnight stay. Over their lifetime males ($n = 5$) had more surgery including repair of undescended testicle and circumcision and ruptured appendicitis that included a 5-night stay with a 42 day return to sport. Males were also admitted for at least one night in the hospital that included: ear, nose, and throat referral; concussion and asthma-2-night stay.

A large portion of the athletes (69.2% F; 65.1% M) had contact with their family physician in the past year. Females reported a slightly greater number ($n = 102$) of allied health care, sport medicine visits and x-rays appointments when compared to males ($n = 65$) (see **Table 8**).

TABLE 7 | Reported use of supplements separated by sex.

Supplement	F = 52		M =44	
	n	%	*n*	%
Vitamin D	11	21.1	7	15.9
Multivitamin	9	17.3	5	11.3
Omega 3	3	5.7	2	4.4
Probiotics	1	1.9	3	6.8
Magnesium			2	4.5
Vitamin C	4	7.6		
Vitamin A and B	1	1.9		
Calcium	1	1.9		
Melatonin	1	1.9		
Iron Feramax			1	2.2

TABLE 8 | Practitioner utilization over the past 12 months (excluding hospitals visits) separated by sex.

Practitioners and services	F = 52		M = 44	
	n	%	*n*	%
Physician—emergency room doctor	14	26.9	14	31.8
Physician—general practitioner/ family	36	69.2	28	63.6
Physician—sport medicine doctor	4	7.7	1	2.3
Surgeon	0	0.0	4	9.0
Physiotherapist	10	19.2	3	6.8
Chiropractor	8	15.4	3	6.8
Massage therapist	9	17.3	4	9.0
Athletic therapist	1	1.9	1	2.3
Magnetic resonance imaging (MRI)	2	3.8	0	0.0
Computer tomography (CT scan)	3	5.8	0	0.0
Radiographs (x-rays)	11	21.2	7	15.9
Other (please specify)	4			
Total no of visits	**102**		**65**	

DISCUSSION

We report on 96 athletes who represent 26.4% of the 363 ski racers registered across all clubs in the AASA age groups of U12 and U14 in 2017 (http://albertaalpine.ca/wp-content/uploads/2017/05/AASA-Membership-Statistics-2017.pdf). When compared to a group of provincial level Austrian ski racers (mean age M 12.3 ± 1.2, F 12.4 ± 1.3 yrs.; body weight (kg) M 44.1 ± 9.2, F 46.8 ± 10.8; height (cm) M 153.6 ± 9.4, F 155.4 ± 9.6; and BMI (kg/m^2) M 18.5 ± 2.2, F 19.1 ± 2.6), our racers (see **Table 1**), were younger, lighter and not as tall (Müller et al., 2016). Younger age and a club style of training vs. attendance at a full-time ski school academy likely contributed to these differences in body composition.

Ski racers in Western Canada are primarily supported by their parents and coaches working in collaboration to ensure they have the best opportunity to achieve their potential. The cost burden of competing is paid entirely by parents through the club model typical of Canadian ski racing. Clubs are incorporated under the Societies Act which permits some retained earnings but otherwise requires dollars to be spent toward declared objectives. These objectives include payment of coaches through salaries, gym rental, on hill training such as lane space, equipment etc., and all of these costs are passed on to parents and subsequently recovered from their registration fees. Therefore, have high levels of education because of the association with better economic outcomes is both common and a necessity for parents of racers. This higher level of education and higher household income is not just associated with ski racing (PBM, 2016), but with all sport participation in Canada (Statistics Canada, 2013a,b).

Physical Activity Volume

The primary aim of this present study was to describe the participation of all sport and physical activity outside of physical education classes over three timelines: just prior to the start of pre-season training, over previous 12 months and lifetime. We know that Canadian children (ages 5–12 years) spend a considerable amount of time participating in sports and recreation activities, particularly in the summer months (CFLRI, 2009). These athletes were no different as observed by the large range of activities which included several summer camps within the 6 week period prior to start of the September school year. In terms of commonly participated activities in adolescents, the Canadian Sport Participation Report, lists soccer followed by swimming and ice hockey (2010). However, our athletes, regardless of whether they were female or male, participated in cycling-road/mtn (77%), swimming (53%) and hiking/scrambling (45%). These three activities are associated with warmer weather in Alberta, which is more often in the late summer months of August and September. Many of these athletes also live within close proximity to the mountains, which likely influence their participation in hiking and mountain biking because of the associated physical and social-cultural environment (Bolívar et al., 2010).

The daily recommended amount of physical activity (365 h/year) is not given as an accumulated index of exposure or total volume over a 12 month period, which is a standard in injury surveillance research (Nielsen et al., 2019). However, these athletes self-reported just under 400 h of activity (range females 27–1,015; males 62–869 h), and therefore easily meet both the World Health Organization (2010) and Canadian recommended 60 min of daily PA for their age group (2018).

The athlete's total participation hours included dedicated time on snow (November-May), which from a skill acquisition is important during the adolescent years based on Alpine Canada's program LTAD (2019). The Training and Competition Focus Matrix states that U10 should have 10–15 days on snow with 50–65% free ski volume training and U14 should have 15–30 days on snow with 40–50% of their training time dedicated to technical and tactical skiing skills. Our racers easily met these criteria with an average of 20 days on snow and much of their training involved off-piste skiing because of the positive snow and terrain conditions in the Rocky Mountains.

To be a strong and fast skier at the elite level requires participation in a variety of training forms outside of on snow training (Gilgien et al., 2018). The current literature related to young athletes also focuses on avoiding early specialization (Post et al., 2017). Somewhat surprisingly, 15.5% (15/96) of the athletes reported over 480 h of skiing over the previous year. Three of these athletes (F) reported 650 plus hours of dedicated alpine skiing, and this could be viewed as an excessive amount for 10–14 year old's, even if it is at a low intensity (Faigenbaum, 2019). The highest total volume of PA at 1,015 h was reported by a U14 female athlete which included the second most total hours of alpine skiing (720 h). This athlete participated in a variety of activities that included badminton (5 h), figure skating (30 h), golf (192 h), tennis (15 h), and weight training (32 h). Like others she also did cycling (20 h) and running (1 h). She sustained a lower body injury (MCL strain) in the following year (2018) that required 4 weeks of physio before she returned to activity. Launay (2015) states that overextending physically, can result in overuse injuries to the musculoskeletal system and perhaps this large volume in weekly sports and activities in combination with ski training and competition contributed to her injury. This outcome is supported by Räisänen et al. (2016) in a study that showed higher PA participation frequency and intensity increased the risk of injury and that injury prevalence was typically highest in sports club activities (2016).

Fundamental Movement Skills

Developing skiers require a large FMS repertoire which includes training of coordination /motor control, balance and quickness. This type of "training smarter" involves off snow imitation of skiing associated with a variety of activities such as cycling, running (on uneven terrain) and soccer (football) (Raschner et al., 2004; Gabbett, 2016). All ski clubs in this study encouraged athletes to participant in activities outside of skiing and the mean number of those participated in by our athletes was four. Clubs also incorporated strength and balance activities into their dryland and preseason training programs beyond just running and games of soccer. Recent research states that cycling, one of the favorite activities among our athletes not only contributes to balance but is also a cognitively-engaging exercise and has a stronger effect on executive function when compared to other aerobic exercise (Best, 2010; Leyland et al., 2019). Therefore, the athletes in the ski club system were exposed to a variety of activities outside of on-snow training, helping to develop their FMS proficiency, which is advocated for in the Canadian Alpine LTAD model.

Injuries

The secondary aim of this study was to provide insight into the injuries reported and health indicators in adolescent youth ski racers over the past 12 months or a lifetime. In Canada, two out of three (66%) injuries among adolescents reportedly are linked to sport and this age group has a higher percent of fractures (21%), lower limb (33%) hand and wrist (22%) injuries when compared to older adults in Canada (Billette and Janz, 2015). Most growth plate fractures happen from falling and twisting and are common in fast moving sports such as skiing and biking (Malina et al., 2004). Therefore, it is not surprising based on our athletes' activities that there were several reported cases of these injuries (see **Tables 4**, **5**) with the knee and ankle as the most common locations (Malina et al., 2004).

It is interesting to note that ice hockey, rugby and ringette are sports with the highest proportion of brain injuries among children aged 5–19 years (CHIRPP, 2018). Due to a growing concern around concussion management in youth alpine skiing, the AASA implemented an updated concussion policy effective in the 2016–17 seasons. This policy stated that if a coach suspected a concussion then the athlete should be immediately removed from the hill and their pass suspended until physician clearance was received by the organization. It also mandated coach education and required parents to sign that they acknowledge the policy. This may have resulted in greater awareness and as such the number of concussions (4%) reported by athletes was considerably less than other non-concussive injuries (16.6%) reported in 2017.

Diagnosis of Attention Deficit-Hyperactivity Disorder (ADHD) and Learning Issues

Sports in general provide a positive experience for adolescents with ADHD with evidence showing a statistically significant decrease in markers of anxiety and depression with higher levels of sports participation (Kiluk et al., 2009; Perrin and Jotwani, 2014). The male athletes had a greater number of reported attention or learning issues when compared to females in our study. The prevalence of ADHD in student and elite athletes is between 7 and 8% (Han et al., 2019) with symptoms often surfacing just prior to the age of 12 (Thomas et al., 2015). Given that there is a positive experience with sport participation the prevalence in youth athletes maybe greater than in the general population (Poysophon and Rao, 2018). To the best of our knowledge this is the first reporting of the prevalence ADHD in young alpine skiers.

Reactive Airway and Asthma

Airway disease has been reported in the literature as the most frequently encountered chronic respiratory condition in athletes (Hull et al., 2012) however, there are only a few reported studies related to alpine skiing. The prevalence of exercise-induced asthma (EIA) or exercise-induced bronchoconstriction (EIB) occurs in about 15% of cross-country skiers in comparison with a <4%, in alpine skiing and ski jumping despite training in similar weather conditions (Karjalainen et al., 2000). Asthma is the most common chronic disease affecting children in Alberta and EIA is a general concern during growth and development according to The Wellbeing Report of Canada's Young Children (2011). Our athletes reported a frequency (12.5%), more similar to cross-country skiers however Alberta is known for very dry air conditions. Therefore, it may not be unexpected to have a greater prevalence of EIA or reactive airway conditions in young alpine skiers given the amount of time they spend in the outdoors.

Supplements

Supplemental vitamin and mineral (VM) use are common among adult Canadians, and more prevalent among those with healthier lifestyles and of socio-economically advantaged backgrounds (Guo et al., 2009). According to Health Canada: (2015) supplement use in those aged 9–13 years is 36.8% and teenage females use more than males (32.9% vs. 26.5%). The province of Alberta has the highest rate of VM supplemental use among children and teenagers at 54.1% (Health Canada, 2015). Our study results demonstrate similar trends as the above with over the half the athletes (53.6%) taking supplements and female (59%) consuming more than the males 46.5%.

Utilization of Practitioners and or Services

Previous research shows that participating in organized sports is a major risk factor for hospitalization throughout adolescence (Mattila et al., 2009) and the Canadian sport and athletic statistics identify males as being hospitalized more often due to injury than females (National Ambulatory Care Reporting System 2017–2018, 2019). A similar a pattern of emergency room visits occurred with our athletes but with limited overnight stays and those that were hospitalized included only males (CIHI, 2019). The emergency room visits involved sport and activity related injuries as well as a variety of other health reasons. Given our athletes ages this is not unusual as the top pediatric visits, other than injuries, typically include poisonings, breathing problems, neurological, infections and gastrointestinal problems; all of which, with the exception of poisoning these athletes experienced.

The majority of the athletes (68%, $n = 64$) visited their family physicians in the past year. This was slightly greater than the Canadian frequency of 60% in the age group of 12–17 years old (Statistics Canada, 2018). Generally, provider contact in this age group is related to non-preventative care visits vs. preventive care visits (Nordin et al., 2010), and many of the athletes in this study saw other providers for a variety of treatment care (athletic therapist, chiropractor, massage therapist and physiotherapist).

STRENGTHS AND LIMITATIONS

To the best of our knowledge, this is one of only a few studies (Müller et al., 2017c), investigating self-report PA, injury and illness health surveillance data in this age group of alpine skiers. However, information bias often accompanies self-report data and previous literature has shown that a short recall period is preferable to a long one, particularly when asking participants about routine or frequent events (Althubaiti, 2016). Our questionnaire had three time periods which may have resulted in overlap of the reporting and given this we should have paid more attention educating parents on how to complete the forms. This may have reduced some of the missing data and improved the quality of data particularly related to intensity of activity, which was poorly filled in.

We recognize that the alpine skiing community is interested in understanding the impact and timing of training load which has been identified as a valuable modifiable risk factor for injury (Gabbett, 2016). Our volume calculation of PA was based on the number of hours spent each week in ski training and other recreational physical activities outside of PE classes, and is at best a crude approach, although practical. However, if volume could be combined with a perceived exertion rating, determination of training load could occur (Wallace et al., 2017). This combination of volume and intensity of activity (total load) should be considered since many 10–14 year old athletes are entering their growth period which is associated with an increased risk of overuse injuries (Bahr, 2014; Jayanthi et al., 2015). Feasibility is also important and therefore future research should consider wearable devices to measure PA volume objectively with accelerometers and or in combination with a Global Positioning System so to measure how individual training loads change over time (Drew and Finch, 2016).

Lastly, the use of common measures for the assessment of modifiable risk factors and health outcomes is necessary for future comparison. In this cross-sectional study the data collection occurred through each ski club, which was very labor intensive from the researchers and the club personnel perspectives. Similar to previously published studies in winter sports (Niedermeier et al., 2019), we acknowledge the limitations connected to a cross-sectional study based on self-reports (e.g., impossible to assess causal relationships, non-truthfully answered questions, or a potential recall bias). The implementation of a centralized system through the ASSA or Alpine Canada Association with an online version of the baseline medical questionnaire would streamline the process.

CONCLUSION

In conclusion, adolescent alpine ski racers in Western Canada were exposed to many hours of physical activity and participated in several different sports outside of ski training and physical education classes; all of which contribute to their fundamental movement skills. The accumulated volume of physical activity from ski training over the previous 12 months and all other physical activities was higher than the Canadian recommended guidelines of 60 min of daily PA for their age group (2018). This study did not report on intensity of physical activity and therefore future research should consider monitoring the combination of volume and intensity to identify whether this age group of ski racers could be at risk of overextending themselves physically.

The outcomes from the baseline medical questionnaire highlighted a typical pattern of injuries, common health issues and practitioner visits related to this age group when compared to the population at large. However, athletes that suffered an injury did lose participation hours particularly when related to lower leg injuries, and therefore strategies to prevent these injuries is an important consideration (Öztürk and Kılıç, 2013). Future research directions should consider an easily accessible on-line health and injury surveillance questionnaire in combination with wearable technology so as to better quantify training load across all sport and physical activities in 10–14 year-old Canadian alpine ski club racers.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by The Conjoint Health Research Ethics Board (CHREB), University of Calgary reviewed and approved the following research protocol: Ethics ID: REB16-1818. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

PD-B designed the study, collected and analyzed the data. CE contributed to study proposal development, contributed to study design and critically reviewed the edited manuscript before submission.

FUNDING

This research was funded through a special grant through the Faculty of Kinesiology Dean's office.

ACKNOWLEDGMENTS

We would like to acknowledge the support of the Sport Injury Prevention Research Centre (SIPRC), their research coordinators CVB, KK and the research assistants who entered the data, as well undergraduate kinesiology student RS for ensuring that the forms were collected. Thank you to the ski club parents and racers who completed the forms for this study.

REFERENCES

Al-Sahab, B., Ardern, C. I., Hamadeh, M. J., and Tamin, H. (2010). Age at menarche in Canada: results from the National longitudinal survey of children and youth. *BMC Public Health* 10:736. doi: 10.1186/1471-2458-10-736

Althubaiti, A. (2016). Information bias in health research: definition, pitfalls, and adjustment methods. *J. Multidiscip. Healthc.* 9, 211–217. doi: 10.2147/JMDH.S104807

Anderson, N. K., Horan, M., Doran, G., De Luke, G., Millet, P. J. (2019). Injury patterns in the high-risk sport of elite youth alpine ski racing. *Orthop J Sports Med.* 7(suppl 5):2325967119S0042. doi: 10.1177/2325967119S00420

Bahr, R. (2014). Demise of the fittest: are we destroying our biggest talents? *Br. J. Sports Med.* 48, 1265–1267. doi: 10.1136/bjsports-2014-093832

Bakhos, L. L., Lockhart, G. R., Myers, R., and Linakis, J. G. (2010). Emergency department visits for concussion in young child athletes. *Pediatrics* 126, e550–e556. doi: 10.1542/peds.2009-3101

Best, J. R. (2010). Effects of physical activity on children's executive function: contributions of experimental research on Aerobic exercise. *Dev. Rev.* 30, 331–551. doi: 10.1016/j.dr.2010.08.001

Billette, J. M., and Janz, T. (2015). *Injuries in Canada: Insights From the Canadian Community Health Survey Statistics Canada Catalogue no. 82-624-X.* Available online at: https://www150.statcan.gc.ca/n1/pub/82-624-x/2011001/article/11506-eng.htm (accessed September 2, 2019).

Bolívar, J., Daponte, A., Rodríguez, M., and Sánchez, J. J. (2010). The influence of individual, social and physical environment factors on physical activity in the adult population in Andalusia, Spain. *Int. J. Environ. Res. Public Health* 7, 60–77. doi: 10.3390/ijerph7010060

Cairney, J., and Veldhuizen, S. (2017). Organized sport and physical activity participation and body mass index in children and youth: a longitudinal study. *Prev. Med. Rep.* 6, 336–338. doi: 10.1016/j.pmedr.2017.04.005

Canadian Physical Activity Guidelines (2018). *Participaction Report Card on Physical Activity for Children and Youth.* Available online at: https://www.participaction.com/en-ca/resources/report-card (accessed September 2, 2019).

CFLRI (2009). *Physical Activity and Sport Monitors (Population Studies).* Available online at: http://www.cflri.ca/physical-activity-and-sport-monitors-population-studies (accessed October, 2, 2019).

CHIRPP (2018). *Canadian Hospitals Injury Reporting and Prevention Program*. Available online at: https://www.canada.ca/en/public-health/services/diseases/concussion-sign-symptoms/concussion-sport-infographic.html (accessed December, 2, 2019).

CIHI (2019). *Hospital Morbidity Database 2017-2018.* Available online at: https://www.cihi.ca/en/access-data-and-reports/make-a-data-request (accessed September 15, 2019).

Comeau, M. E., Bouchard, D. R., Levesque, C., Johnson, M. J., Rioux, B. V., Mayo, A., et al. (2017). Association between functional movements skills and health indicators in children aged between 9 and 12 years old. *Int. J. Environ. Res. Public Health* 14:1010. doi: 10.3390/ijerph14091010

Doyle-Baker, P. K., Kashluba, K., and Clark, M. (2017). "Evaluation of a current dryland training program in alpine ski racers under 14 years," in *Science and Skiing*, eds E. Mueller, J. Kroll, S. Lindinger, J. T. Pfusterschmied, and V. I. Stoggl (Salzburg: Meyer and Meyer), 77–85.

Drew, M. K., and Finch, C. F. (2016). The relationship between training load and injury, illness and soreness: a systematic and literature review. *Sports Med.* 46, 861–883. doi: 10.1007/s40279-015-0459-8

Duncan, M. J., Bryant, E., and Stodden, D. (2016). Low fundamental movement skill proficiency is associated with high BMI and body fatness in girls but not boys aged 6–11 years old. *J. Sports Sci.* 35, 2135–2141. doi: 10.1080/02640414.2016.1258483

Emery, C. A., Rose, M. S., McAllister, J. R., and Meeuwisse, W. H. (2007). A prevention strategy to reduce the incidence of injury in high school basketball: a cluster randomized controlled trial. *Clin. J. Sport. Med.* 17, 17–24. doi: 10.1097/JSM.0b013e31802e9c05

Faigenbaum, A. D. (2019). Overtraining in young athletes: how much is too much? *ACSM Health Fitness J.* 13, 8–13. doi: 10.1249/FIT.0b013e3181aae0a0

Gabbett, T. J. (2016). The training-injury prevention paradox: should athletes be training smarter and harder. *Br. J. Sports Med.* 50, 273–280. doi: 10.1136/bjsports-2015-095788

Gilgien, M., Reid, R., Raschner, C., Supej, M., and Holmbrg, H. C. (2018). The training of olympic alpine ski racers. *Front. Physiol.* 9:1772. doi: 10.3389/fphys.2018.01772

Guo, X., Willows, N., Kuhle, S., Jhangri, G., and Veugelers, P. J. (2009). Use of vitamin and mineral supplements among canadian adults. *Can. J. Public Health* 100, 357–360. doi: 10.1007/BF03405270

Han, D. H., McDuff, D., Thompson, D., Hitchcock, M. E., Reardon, C. L., and Hainline, B. (2019). Attention-deficit/hyperactivity disorder in elite athletes: a narrative review. *Br. J. Sports Med.* 53, 741–745. doi: 10.1136/bjsports-2019-100713

Harris, P. A., Taylor, R., Thielke, R., Payne, J., Gonzalez, N., and Conde, J. G. (2009). Research electronic data capture (REDCap)–a metadata-driven methodology and workflow process for providing translational research informatics support. *J. Biomed. Inform.* 42, 377–381. doi: 10.1016/j.jbi.2008.08.010

Health Canada (2015). *Use of Nutritional Supplements, 2015.* Available online at: https://www150.statcan.gc.ca/n1/pub/82-625-x/2017001/article/14831-eng.htm (accessed September 2, 2019).

Henrique, R. S., Re, A. H., Stodden, D. F., Fransen, J., Campos, C. M., Queiroz, D. R., et al. (2016). Association between sports participation, motor competence and weight status: a longitudinal study. *J. Sci. Med. Sport*s 19, 825–829. doi: 10.1016/j.jsams.2015.12.512

Hull, J. H., Ansley, L., Robson-Ansley, P., and Parsons, J. P. (2012). Managing respiratory problems in athletes. *Clin. Med.* 12, 351–356. doi: 10.7861/clinmedicine.12-4-351

Jaakkola, T., Yli-Piipari, S., Huotari, P., Watt, A., and Liukkonen, J. (2016). Fundamental movement skills and physical fitness as predictors of physical activity: a 6-year follow-up study. *Scand. J. Med. Sci. Sports*. 26, 74–81. doi: 10.1111/sms.12407

Jayanthi, N. A., LaBella, C. R., and Fischer, D. (2015). Sports-specialized intensive training and the risk of injury in young athletes: a clinical case-control study. *Am. J. Sports Med.* 43, 794–801. doi: 10.1177/0363546514567298

Karjalainen, E. M., Laitinen, A., Sue-Chu, M., Altraja, A., Bjermer, L., and Laitinen, L. A. (2000). Evidence of airway inflammation and remodeling in ski athletes with and without bronchial hyperresponsiveness to methacholine. *Am. J. Respir. Crit. Care Med.* 161, 2086–2091. doi: 10.1164/ajrccm.161.6.9907025

Kiluk, B. D., Weden, S., and Culotta, V. P. (2009). Sport participation and anxiety in children with ADHD. *J. Atten. Disord.* 12, 499–506. doi: 10.1177/1087054708320400

Launay, F. (2015). Sport-related overuse injuries in children. *Orthop Traumatol-Sur.* 101, 139–147. doi: 10.1016/j.otsr.2014.06.030

Leyland, L.-A., Spencer, B., Beale, N., Jones, T., and van Reekum, C. M. (2019). The effect of cycling on cognitive function and well-being in older adults. *PLoS ONE* 14:e0211779. doi: 10.1371/journal.pone.0211779

Lloyd, M., Saunders, T. J., Bremer, E., and Tremblay, M. S. (2014). Long-term importance of fundamental motor skills: a 20-year follow-up study. *Adapt. Phys. Act. Quart.* 31, 67–78. doi: 10.1123/apaq.2013-0048

LTAD (2019). *Alpine Canada Long Term Athlete Development Model.* Available online at: https://ltad.alpinecanada.org/stages/learn-to-train

Lubans, D. R., Morgan, P. J., Cliff, D. P., Barnett, L. M., and Okely, A. D. (2010). Fundamental movement skills in children and adolescents: review of associated health benefits. *Sports Med.* 40, 1019–1035. doi: 10.2165/11536850-000000000-00000

Malina, R. M., Bouchard, C., and Bar-Or, O. (2004). *Growth, Maturation, and Physical Activity*, 2nd Edn. Champaign, IL: Human Kinetics, 267–273.

Mattila, V. M., Parkkari, J., and Koivusilta, L. (2009). Participation in sports clubs is a strong predictor of injury hospitalization: a prospective cohort study. *Scand. J. Med. Sci. Sport*. 19, 267–273. doi: 10.1111/j.1600-0838.2008.00800.x

Müller, L., Gonaus, C., Perner, C., Müller, E., and Raschner, C. (2017a). Maturity status influences the relative age effect in national top-level youth alpine ski racing and soccer. *PLoS ONE* 12:e0181810. doi: 10.1371/journal.pone.0181810

Müller, L., Hildebrandt, C., Müller, E., Fink, C., and Raschner, C. (2017b). Long-term athletic development in youth alpine ski racing: the effect of physical fitness, ski racing technique, anthropometrics and biological maturity status on injuries. *Front. Physiol.* 8:656. doi: 10.3389/fphys.2017.00656

Müller, L., Hildebrandt, C., Müller, E., Oberhoffer, R., and Raschner, C. (2017c). Injuries and illnesses in a cohort of elite youth alpine ski racers and the influence of biological maturity and relative age: a two-season prospective study. *Open Access J. Sports Med.* 8, 113–122. doi: 10.2147/OAJSM.S133811

Müller, L., Hildebrandt, C., and Raschner, C. (2015). The relative age effect and the influence on performance in youth alpine ski racing. *J. Sports Sci. Med.* 14, 16–22.

Müller, L., Müller, E., Hildebrandt, C., and Raschner, C. (2016). Biological maturity status strongly intensifies the relative age effect in Alpine Ski racing. *PLoS ONE* 11:e0160969. doi: 10.1371/journal.pone.0160969

National Ambulatory Care Reporting System 2017–2018 (2019). *Sport and Athletic Statistics in Canadian Institute for Health Information.* Available online at: https://www.cihi.ca/en/access-data-and-reports/make-a-data-request (accessed September 15, 2019).

Nelson, L. D., Guskiewicz, K. M., Marshall, S. W., Hammeke, T., Barr, W., Randolph, C. P., et al. (2016). Multiple self-reported concussions are more prevalent in athletes with adhd and learning disability. *Clin. J. Sport Med.* 26, 120–127. doi: 10.1097/JSM.0000000000000207

Niedermeier, M., Ruedl, G., Burtscher, M., and Kopp, M. (2019). Injury-related behavioral variables in alpine skiers, snowboarders, and ski tourers—a matched and enlarged re-analysis. *Int. J. Environ. Res. Public Health* 16:3807. doi: 10.3390/ijerph16203807

Nielsen, R. O., Bertelsen, M. L., Ramskov, D., Møller, M., Hulme, A., Theisen, D., et al. (2019). Time-to-event analysis for sports injury research part 1: time-varying exposures. *Br. J. Sports Med.* 53, 61–68. doi: 10.1136/bjsports-2018-099408

Nordin, J. D., Solberg, L. I., and Parker, E. D. (2010). Adolescent primary care visit patterns. *Ann. Fam. Med.* 8, 511–516. doi: 10.1370/afm.1188

O'Brien, W., Belton, S., and Issartel, J. (2016). The relationship between adolescents' physical activity, fundamental movement skills and weight status. *J. Sports Sci.* 34, 1159–1167. doi: 10.1080/02640414.2015.1096017

Öztürk, S., and Kılıç, D. (2013). What is the economic burden of sports injuries? *Eklem Hastalik Cerrahisi*. 24, 108–111. doi: 10.5606/ehc.2013.24

PBM (2016). *Canadian Ski Council's Facts and Stats, Print Measurement Bureau 2014 - 2015 year database.* Available online at: https://www.skicanada.org/wp-content/uploads/2016/01/2014-15-Facts-and-Stats.pdf (accessed January 4, 2020).

Perrin, A. E., and Jotwani, V. M. (2014). Addressing the unique issues of student athletes with ADHD. *J. Fam. Pract.* 63, E1–E9.

Pol, R., Hristovski, R., Medina, D., and Balague, N. (2019). From microscopic to macroscopic sports injuries. Applying the complex dynamic systems approach to sports medicine: a narrative review. *Br. J. Sports Med.* 53, 1214–1220. doi: 10.1136/bjsports-2016-097395

Post, E. G., Trigsted, S. M., Riekena, J. W., Hetzel, S., McGuine, T. A., Brooks, M. A., et al. (2017). The association of sport specialization and training volume with injury history in youth athletes. *Am. J. Sports Med.* 45, 1405–1412. doi: 10.1177/0363546517690848

Poysophon, P., and Rao, A. L. (2018). Neurocognitive deficits associated with ADHD in athletes: a systematic review. *Sports Health* 10, 317–326. doi: 10.1177/1941738117751387

Räisänen, A. M., Parkkari, J., Karhola, L., and Rimpel, A. (2016). Adolescent physical activity-related injuries in sports club, school sports and other leisure time physical activities. *Cogent. Med.* 3:260786. doi: 10.1080/2331205X.2016.1260786

Raschner, C., Müller, E., Schwameder, H., Haid, C., and Männel, D. (1995). The influence of anthropometric characteristics on the performance in slalom in adolescent ski racers," *in Sports Performance and Training*, eds J. Krug and H. Minow (Sankt Augustin: Academia), 341–346.

Raschner, C., Patterson, C., and Müller, E. (2004). "Coordination and stabilization-oriented strength training with multifunctional training devices in a long-term training program of young Austrian ski racers," in *Proceedings of the 3rd International Congress on Skiing and Science*, eds D. Bacharach and D. Seifert (Snowmass: St. Cloud State University), 93–94.

Richmond, S. A., Kang, J., Doyle-Baker, P. K., Nettel-Aguirre, A., and Emery, C. A. (2016). A school-based injury prevention program to reduce sport injury risk and improve healthy outcomes in youth: a pilot cluster-randomized controlled trial. *Clin. J. Sport Med.* 26, 291–298. doi: 10.1097/JSM.0000000000000261

Robinson, L. E., Stodden, D. F., Barnett, L. M., Lopes, P., Logan, S. W., Rodrigues, L. P., et al. (2015). Motor competence and its effect on positive developmental trajectories of health. *Sports Med.* 45, 1273–1284. doi: 10.1007/s40279-015-0351-6

Spörri, J., Kröll, J., Gilgien, M., and Müller, E. (2017). How to prevent injuries in alpine ski racing: what do we know and where do we go from here? *Sports Med.* 47, 599–614. doi: 10.1007/s40279-016-0601-2

Statistics Canada (2013a). *Injuries in Canada: Insights from the Canadian Community Health Survey, 2013.* Available online at: http://www.statcan.gc.ca/pub/82-624-x/2011001/article/11506-eng.htm (accessed August 30, 2019).

Statistics Canada (2013b). *Sport Participation 2010 Research Paper*. Available online at: http://publications.gc.ca/collections/collection_2013/pc-ch/CH24-1-2012-eng.pdf (accessed September 1, 2019).

Statistics Canada (2018). *Table 13-10-0096-16. Has a Regular Healthcare Provider, by Age Group.* Available online at: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1310009616 (accessed October 5, 2019).

The Wellbeing Report of Canada's Young Children (2011). Available onmline at: http://www.dpe-agje-ecd-elcc.ca/eng/ecd/well-being/sp_1027_04_12_eng.pdf (accessed September 3, 2019).

Thomas, R., Sanders, S., Doust, J., Beller, E., and Glasziou, P. (2015). Prevalence of attention-deficit/hyperactivity disorder: a systematic review and meta-analysis. *Pediatric* 135, e994–e1001. doi: 10.1542/peds.2014-3482

Tremblay, M. S., Carson, V., Chaput, J. P., Connor Gorber, S., Dinh, T., Duggan, M., et al. (2016). Canadian 24-hour movement guidelines for children and youth: an integration of physical activity, sedentary behaviour, and sleep. *Appl. Physiol. Nutr. Me.* 41, S311–S327. doi: 10.1139/apnm-2016-0151

Wallace, S., Jordan, M., Blake, T., and Doyle-Baker, P. (2017). Heart rate variability in an elite female alpine skier: a case study. *Ann. Appl. Sport Sci.* 5, 3–10. doi: 10.18869/acadpub.aassjournal.5.2.3

Warda, L. J., and Yanchar, N. L. (2012). Canadian paediatric society, injury prevention Committee. Abridged version. *Paediatric Child Health.* 17, 35–36. doi: 10.1093/pch/17.1.35

Williams, H. G., Pfeiffer, K. A., O'Neill, J. R., Dowda, M., McIver, K. L., Brown, W. H., et al. (2008). Motor skill performance and physical activity in preschool children. *Obesity* 16, 1421–1426. doi: 10.1038/oby.2008.214

World Health Organization (2010). *WHO and the International Olympic Committee Signed Agreement to Improve Healthy Lifestyles.* Available online at: http://www.who.int/mediacentre/news/releases/2010/ioc_20100721/en/index.html (accessed September 21, 2019).

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.

frontiers in Sports and Active Living

ORIGINAL RESEARCH
published: 15 May 2020
doi: 10.3389/fspor.2020.00056

On-Field Ski Kinematic According to Leg and Discipline in Elite Alpine Skiers

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Edited by:
Jörg Spörri,
Balgrist University
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Reviewed by:
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Kerstin Witte,
Otto von Guericke University
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Specialty section:
This article was submitted to
Sports Science, Technology and
Engineering,
a section of the journal
Frontiers in Sports and Active Living

Received: 05 September 2019
Accepted: 20 April 2020
Published: 15 May 2020

Citation:
Alhammoud M, Hansen C, Meyer F, Hautier C and Morel B (2020) On-Field Ski Kinematic According to Leg and Discipline in Elite Alpine Skiers. Front. Sports Act. Living 2:56. doi: 10.3389/fspor.2020.00056

This study used wireless technology to investigate joint kinematic characteristics of the four alpine skiing disciplines. Knee and hip angles were measured in 20 national team alpine skiers during 253 ski runs under FIS regulation, including: 85 Slalom (SL), 123 Giant Slalom (GS), 29 Super Giant Slalom (SG), and 16 Downhill (DH). Data were analyzed by outside (OL, $n = 2{,}087$) and inside leg (IL, $n = 2{,}015$). The proportion of concentric and eccentric phases *(extension and flexion respectively for the knee extensors)* as well as the proportion of the quasi-isometric phase defined between $\pm 20^{\circ}.s^{-1}$ depended on the discipline in interaction with the IL/OL ($p < 0.001$). The results showed a lower knee quasi-isometric duration on OL in SL (11%) than other disciplines (DH: 38%; SG: 42%; GS: 34%, $p < 0.001$, $d > 1.8$), suggesting a highly dynamic style. Quasi-isometric mode was significantly longer on OL than IL in GS (34 vs. 20%, $p < 0.001$, $d = 1.16$) and SG (42 vs. 28%, $p < 0.001$, $d = 1.11$) but was significantly longer on IL than OL in SL (19 vs. 11%, $p < 0.001$, $d = 0.64$). Thus, GS and SG showed similarities, with a significantly faster knee eccentric mean angular velocity on IL compared to OL (GS -58 vs. $-54^{\circ}.s^{-1}$, SG -52 vs. $-45^{\circ}.s^{-1}$, $p < 0.001$, $d \geq 0.22$) whereas SL showed an opposite pattern (-72 vs. $-89^{\circ}.s^{-1}$, $p < 0.001$, $d = 1.10$). The quasi-isometric phase was overlooked in previous studies but is crucial to consider. The current data may be used to train the outside and inside leg specificities incorporating discipline-specific contraction modes and exercises.

Keywords: winter sports, angular velocity, knee angle, knee injury prevention, quasi-isometric contraction

INTRODUCTION

The muscular work of the skier was historically described at slow angular velocity during knee flexion (eccentric work of the knee extensors) and extension phases (concentric work of the knee extensors) (Berg et al., 1995). Eccentric contractions resist the compressive forces while traveling down the slope and were previously reported as both longer and of higher intensity than the concentric actions during turns (Berg et al., 1995). However, equipment design and movement pattern have markedly changed during the last decades, especially with the introduction of parabolic skis (carving) (Raschner et al., 2001). These developments have brought this eccentric predominance into question as quasi-isometric and concentric components have been described during carved turns (Kröll et al., 2015a; Minetti, 2016). For example, it was suggested that the bi-articular *rectus femoris* maintained a nearly constant length in female practicing recreational ski whereas the *vastus lateralis* lengthened during the first phase of inside leg (IL) turn (eccentric work), then shortened during the edge change phase (concentric work) and contracted isometrically on the subsequent outside leg (OL) phase (Kröll et al., 2010). The evolution in the joint kinematic aspects of the ski turn with ski carving has been described in Giant Slalom (GS) (Kröll et al., 2015a) but never in the speed disciplines.

Alpine skiing includes four disciplines, with most skiers specialized in technical [Slalom (SL) and GS] or speed disciplines [Super Giant (SG) and Downhill (DH)] (Gilgien et al., 2018b). The GS often serves as a midpoint between SL and SG/DH (Turnbull et al., 2009) due to the technological limitations in recording speed disciplines. Yet, the principles of "kinematic, kinetic, and neuromuscular correspondence" and "coordinative affinity" (Kröll et al., 2015a) should be taken into consideration for sports-specific training; therefore, exercises must be similar to the movements characterizing the discipline (Müller et al., 2000). Ski-specific exercises for technical training include inline skating (Zeglinksi et al., 1998; Kröll et al., 2005), eccentric bike (Gross et al., 2010), or practice on ski ergometers (Panizzolo et al., 2013; Moon et al., 2015; Stöggl et al., 2018). However, DH skiers may require more prolonged isometric maximum- and endurance-force training whereas SL skiers have a greater need for explosiveness with higher rate of force development and dynamic style (Kröll et al., 2015b).

A "quasi-static" component to skiing was already suggested in the technical disciplines due to evidence of thigh muscles co-contraction (Hintermeister et al., 1995). Nevertheless, the quasi-isometric phase was overlooked in the old studies using a double partition of concentric vs. eccentric phases defined between minimal and maximal or maximal to minimal knee joint angles, respectively (Berg et al., 1995; Berg and Eiken, 1999). In addition, previous studies concentrated on the outside phase of experimentally controlled ski cycles (Berg et al., 1995; Hintermeister et al., 1995; Berg and Eiken, 1999) and limited kinematic information is available on the IL (Kröll et al., 2010, 2015a,b), despite the recognized importance of leg independence in alpine skiing (LeMaster, 2010). In this manuscript, we refer to the "quasi-isometric, eccentric and concentric" phases of the ski cycle at the macroscopic knee joint level which may reflect the behavior of the muscle-tendon unit for the monoarticular muscles (*vastii*), but not for the polyarticular muscles (*rectus femoris* and hamstrings) which are impacted by the hip position (Hawkins and Hull, 1990).

In summary, given the distinct nature of the eccentric/concentric/isometric contraction regimens (Higbie et al., 1996), and in the absence of joint kinematic comparison between disciplines, it appears necessary to study the contraction modes and angle-related parameters specific to leg and discipline in order to reproduce its characteristics during dryland trainings. In this context, the knee angular behavior has been suggested as one of the most important parameters for performance, albeit highly variable when measured at minimum radius of the turns in SL (Pozzo et al., 2010). Recent developments in technology including wireless sensors and miniaturized datalogger have made it possible to continuously record angular behavior during complete ski runs. Therefore, the aim of the current study was to investigate the joint kinematic characteristics of elite alpine skiers according to leg and discipline. It was hypothesized that the discipline and leg will affect the knee and hip angles, the angular velocities and the contraction mode durations. It was further hypothesized that a marked quasi-isometric component would be evidenced in the speed disciplines compared with the technical disciplines.

MATERIALS AND METHODS

Participants

Twenty French national team alpine skiers [9 females (23 ± 2 years, 169 ± 5 cm, 64.3 ± 4.7 kg) and 11 males (24 ± 5 years, 178 ± 7 cm, 76.2 ± 7.0 kg)] participated in this study. Skiers were competing in either World Cup ($n = 13$) or Europa Cup ($n = 7$), as Technicians ($n = 15$) or Speed Specialists ($n = 5$), with an average FIS points of 12 ± 7 (the lower the better). The study was approved by the university ethics board and participants provided written informed consent prior to commencement. All procedures conformed to the standards of the Declaration of Helsinki. Participants were provided with prior medical clearance to compete.

General Procedure

Hip and knee angles as well as center of mass acceleration were synchronously measured during 253 ski runs (85 SL, 123 GS, 29 SG, and 16 DH), whilst participants followed their regular ski training program. A total of 49 skier-sessions were obtained corresponding to the triplet "skier, day of testing and discipline." All data were collected during 2 consecutive winter seasons (2016-2017), in the ski resort of Cerro Castor (Ushuaïa, Argentina). Athletes skied in accordance with FIS regulations including using their own equipment and every run (turn length and gate offset) was timed.

Measurements

Measurement of Angles

Electrogoniometers (SG150, Biometrics, Newport, UK) were positioned on the right knee and hip. The goniometers were individually calibrated on the participants the day before the ski run using a video analysis (kinovea©, www.kinovea.org) based on three positions (standing, seated, crouched) and their location was marked with an indelible marker. Data were recorded at 148.15 Hz via a portable wireless data logger (TPM, Trigno Personnal Monitor, Delsys) using a wireless Trigno Goniometer Adapter (Delsys, Boston, USA). In the absence of filtering consensus in the ski literature, a lowpass filter (4th order, Butterworth) with a cut-off frequency set at 1 Hz was retained after inspection of the data with Fast Fourier Transform and logarithmic Bode plots (**Figure 1**). During SL, this strong filtering induced a discrete mitigation of the angle amplitude without

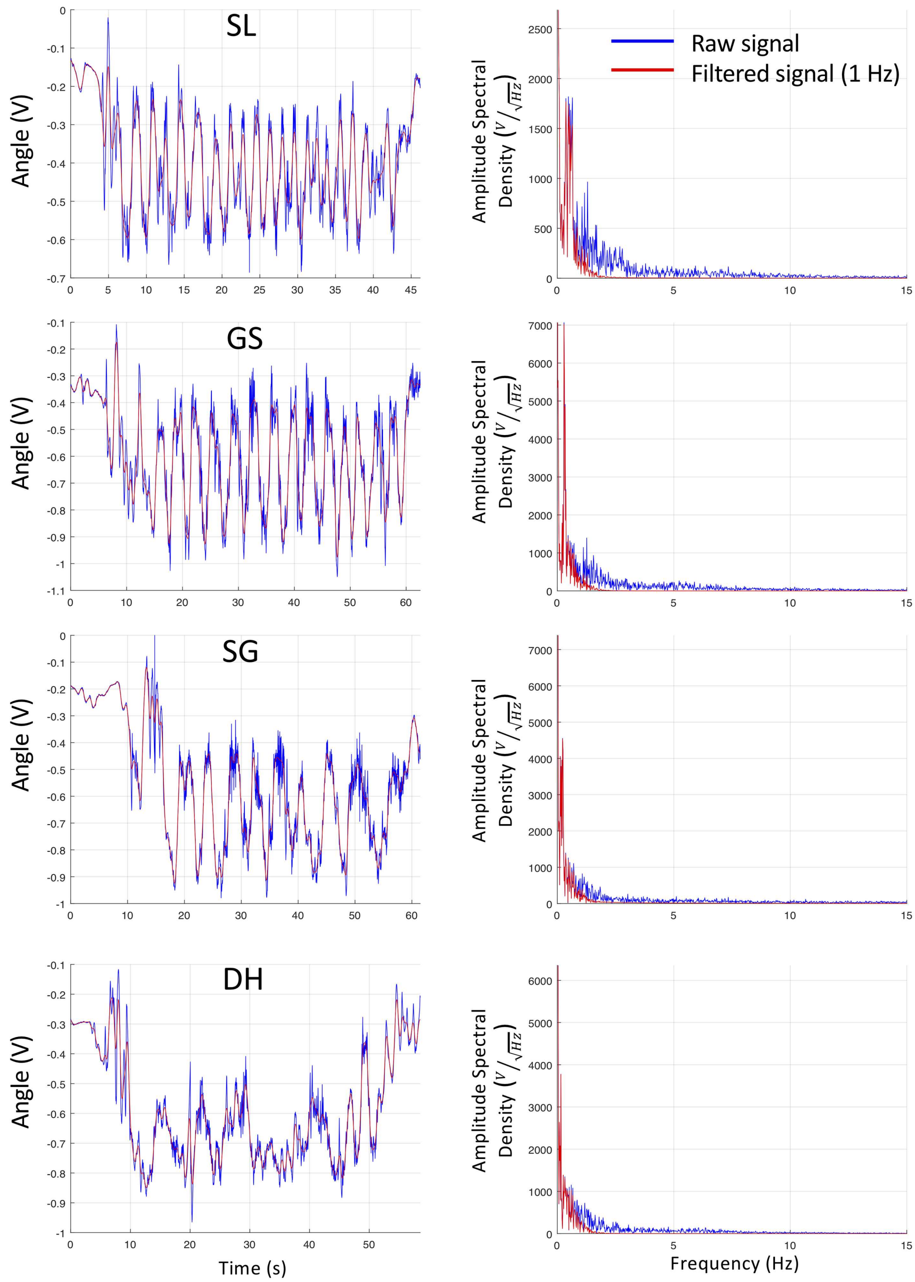

FIGURE 1 | Example of raw and filtered signals in the four alpine disciplines (SL Slalom, GS Giant Slalom, SG Super Giant, DH Downhill). **(Left)** Raw (V) knee angle (blue) and filtered signal (red) in the temporal domain. **(Right)** raw knee angle (blue) and filtered signal (red) in the spectral domain (Fast Fourier Transform) of the amplitude spectral density expressed in V/$\sqrt{Hz}$.

aliasing (**Figure 1**), as the 0.5 Hz spectral component was reduced by 0.5 dB only (i.e., 5% amplitude reduction). Importantly, the chosen filter was very selective (−80 dB/decade), representing a good compromise to protect the useful signal (mean natural frequencies: SL 0.54 Hz, GS 0.34 Hz, SG 0.25 Hz, DH 0.21 Hz) while removing the noise of the unwanted vibrations (2 Hz noise reduced by 24.5 dB, i.e., 94% amplitude reduction **Figure 1**). The phase/frequency relationship of the transfer function filter was constantly equal to zero meaning that there was no temporal distortion as no delay occurred at any frequencies.

Cycle Determination

The TPM was located on the skiers abdomen under the racing suit and tri-axial acceleration was recorded at 148.15 Hz, from which the resultant acceleration (AccR) was determined: $AccR\ (g) = \sqrt{x^2 + y^2 + z^2}$. The AccR was low-pass filtered (fourth-order Butterworth filter with a cut-off frequency of 1 Hz). The minimal (inflection point of the signal derivative) was used to automatically detect the turn switch (Supej et al., 2003; Fasel et al., 2016). This offered good turn detection in all disciplines without noise contamination by the vibrations of the material and/or the slope, as frequencies over 2 Hz have been identified as undesirable vibrations during carving (Nemec et al., 2001).

The data were time-normalized to 100% of each IL/OL. The first/last cycles and the figures (double or triple gates, banana, jumps) were discarded from the analyses to account for the push-off phase and remove the specific characteristics of the figures. Maximal acceleration was not reached after the first gate but the knee angle curves were already in the variability range of the following cycles after two turns (one cycle). There were a few occurrences of goniometer's signal issues (e.g., broken after pole contact) and the corresponding data were systematically discarded. A total of 2087 OL/2015 IL were analyzed for the knee including 686/639 SL, 1113/1157 GS, 221/166 SG, and 67/53 DH. A total of 1599 OL/1581 IL were analyzed for the hip including 482/465 SL, 948/988 GS, 151/104 SG, and 18/24 DH.

Data Analysis

The minimum and maximum angles were computed on the IL and OL for the right knee and hip. As skiing involves resisting gravity and compression, the movement of flexion was assumed to occur in eccentric mode and extension in concentric mode for the knee extensors (Berg et al., 1995; Federolf et al., 2009; Kröll et al., 2015a). Indeed, due to centripetal forces the skiers muscles are loaded eccentrically and the control of the kinetic energy occurs via eccentric muscle activity (Vogt and Hoppeler, 2014). This seems to be an inherent principle of alpine skiing (Vogt and Hoppeler, 2014). However, during knee flexion, a relaxation of the quadriceps without eccentric activity could theoretically occur. Interpretation of the contraction regimen without EMG activity must therefore be done considering this simplification is often observed in the ski literature (Berg et al., 1995; Federolf et al., 2009; Panizzolo et al., 2013; Kröll et al., 2015b).

The first derivative of the knee angle was used to compute the angular velocity and to define the contraction regimen phases. Angular velocities between $\pm 20^{\circ}.s^{-1}$ were defined as quasi-isometric, containing both slow eccentric and concentric motions. Angular velocities below and above this window (range $= 40^{\circ}.s^{-1}$) were defined as eccentric and concentric, respectively. In other words, a knee flexion contains a slow eccentric motion and a knee extension contains a slow concentric motion both classified as quasi-isometric contraction. Lastly, the minimum and maximum angles were also used to describe the flexion and extension phases (**Table 2**) to allow comparison with previous literature (Berg et al., 1995; Nilsson and Haugen, 2004; Panizzolo et al., 2013).

The absolute (in ms) and relative durations (in % of cycle duration) spent in eccentric (flexion, angular velocity $<-20^{\circ}.s^{-1}$), concentric (extension, angular velocity $>20^{\circ}.s^{-1}$), or quasi-isometric mode (angular velocity between -20 and $+20^{\circ}.s^{-1}$) were analyzed. The maximal and mean eccentric and concentric angular velocities were then computed. Two-dimensional density plots were realized for IL and OL in each discipline. They were created using bivariate histograms to examine at which angular position a given angular velocity mainly occurred. A linear color scale intensity was used to show maximum occurrence normalized per turn phase within each discipline (**Figure 2**).

Statistics

Due to the repeated observations, the measurement independence condition is not fulfilled and a classical analysis of variance cannot be applied. Consequently, a mixed linear model was fitted with a random effect on the skier-session (ID) factor. Fixed effects were analyzed for discipline (DH, SG, GS, and SL) and leg (IL, OL) along with the interaction between these two effects using the following model: $Y \sim$ Discipline + IL_OL + Discipline x IL_OL + (1|ID). For the maximum and minimum angles, the values were extracted from the OL and IL, respectively and analyzed as $Y \sim$ Discipline + (1|ID). This method accounts for data autocorrelation due to the repetition of runs, the intermittent missing data after database cleaning, the unbalanced design between disciplines, and the unequal numbers of IL/OL (Cnaan et al., 1997). Data were log-transformed in case of non-normal distribution (Manning and Mullahy, 2001). Significance of both the simple and interaction fixed effects was evaluated with an analysis of variance (Restricted Maximum Likelihood - REML - estimation). After fitting the linear mixed-effect model, *post-hoc* comparisons were performed among groups with Tukey multiplicity correction. All statistical comparisons were coded in R (R Foundation for Statistical Computing, Vienna, Austria) using the *lmerTest* package (Kuznetsova et al., 2017). Estimated marginal means and *post-hoc* tests were calculated with *emmeans* package (Lenth, 2019). Effect sizes for the *post-hoc* pairwise comparison were calculated as Cohen's d for mixed linear model and evaluated as small ($\geq$0.20), medium ($\geq$0.50), and large ($\geq$0.80) (Westfall et al., 2014; Brysbaert and Stevens, 2018). Data were expressed in mean $\pm$ standard deviation. Significance was set at $p < 0.05$ and trends were discussed when $p < 0.10$.

RESULTS

Angles and Mean Angular Velocity

An example of each alpine skiing disciplines is graphically represented along with the contraction regimen (**Figure 3**).

The effect of discipline was not significant for the knee max angle on OL ($p = 0.070$) or the min angle on IL ($p = 0.161$) (**Table 1**). The hip max angle on OL depended on discipline ($p = 0.014$) with a trend for lower values in DH and SG than GS and SL ($p < 0.090$). The min hip angle on IL did not depend on discipline ($p = 0.117$) (**Table 1**).

The mean knee and hip angular velocities beyond $\pm 20^{\circ}.s^{-1}$ showed an interaction between discipline and leg ($p < 0.001$) (**Table 1**). *Post-hoc* analyses showed that the knee concentric velocity was higher in SL than other disciplines on OL ($p < 0.001$, large effects $d > 1.27$), but not IL ($p > 0.638$, $d \leq 0.25$; except a trend for SL vs. DH $p = 0.073$, medium effect $d = 0.79$). The knee concentric velocity was faster in GS than DH on IL ($p = 0.027$, large effect $d = 0.93$), with only a trend on OL ($p = 0.070$, medium effect $d = 0.75$, **Figure 4**, **Table 1**). The hip concentric velocity on OL was higher in SL than GS ($p = 0.020$, large effect $d = 1.12$) and tended to be higher in SL than DH ($p = 0.094$, large effect $d = 2.34$), without differences on IL ($p > 0.382$, $d \leq 1.56$,

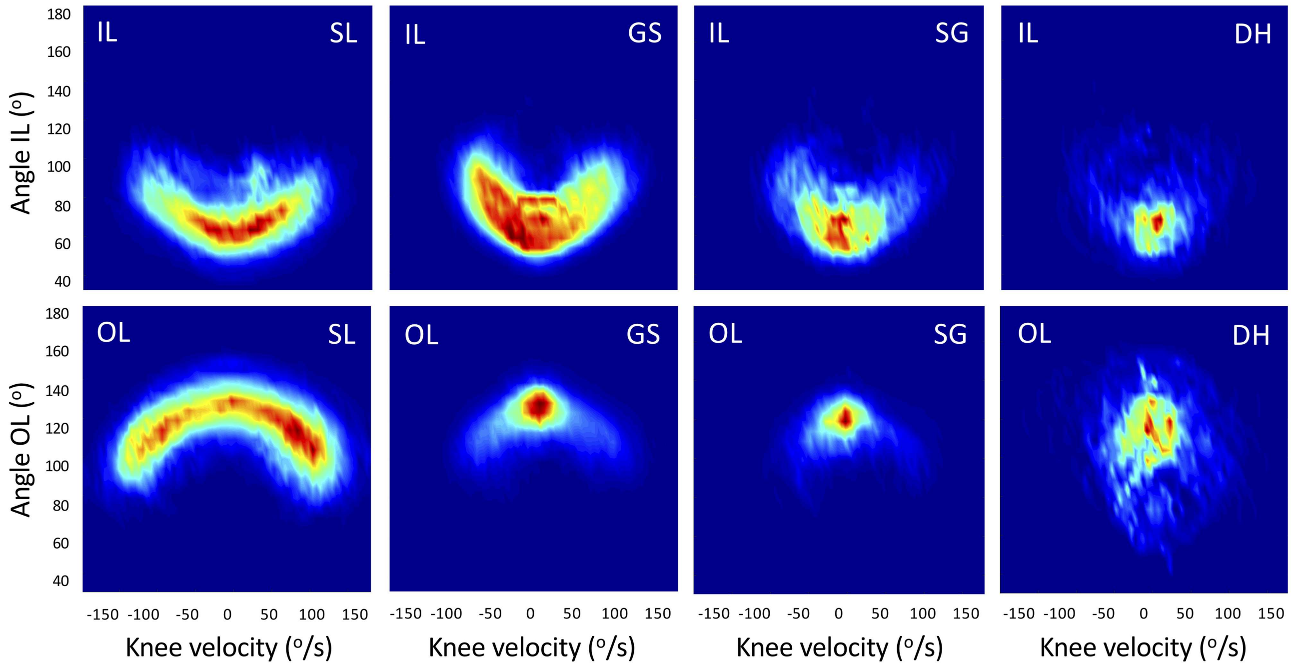

FIGURE 2 | 2D distribution of the knee angular position (y-axis) and velocity (x-axis) for Slalom (SL), Giant Slalom (GS), Super Giant (SG), and Downhill (DH). This representation shows at which angular position a given angular velocity mainly occurred. Deep blue is 0 (no occurrence), dark red is maximum occurrence within the discipline and leg (linear color scale, arbitrary units). IL, inside leg; OL, outside leg.

Figure 4, **Table 1**). In addition, the concentric angular velocity was faster on OL than IL for the knee in SL ($p < 0.001$, large effect $d = 1.36$), and for the hip in SL and SG ($p \leq 0.025$, small to medium effects $d \geq 0.28$); but was faster on IL than OL for the hip in GS ($p < 0.001$, trivial effect $d = 0.19$); without other differences ($p > 0.231$, $d \leq 0.21$, **Figure 4**).

The knee eccentric velocity was significantly higher in SL than other disciplines on both legs ($p < 0.001$, large effects $d > 0.90$, **Figure 4**), and was also higher in GS than SG on OL ($p = 0.018$, medium effect $d = 0.57$) but not IL ($p = 0.218$, small effect $d = 0.35$). The hip eccentric velocity tended to be higher in SL than GS on OL ($p = 0.084$, medium effect $d = 0.78$) but not IL ($p = 0.775$, trivial effect $d = 0.19$). In addition, the eccentric angular velocity was faster on OL than IL for both the knee and hip in SL ($p < 0.001$, large effect knee $d = 1.10$, small effect hip $d = 0.41$); but were faster on IL than OL for the knee in GS, SG, and DH, and for the hip in GS (all $p < 0.001$, small to medium effects $0.22 \leq d \leq 0.56$; except knee in DH $p = 0.051$, small effect $d = 0.34$, **Figure 4**).

The above variables were also calculated without accounting for the quasi-isometric phase (i.e., concentric and eccentric phases based on minimal and maximal knee angles according to Berg et al., 1995) and are presented in **Table 2**.

Absolute Duration of the Concentric, Eccentric, and Quasi-Isometric Phases

The absolute duration of the concentric, quasi-isometric, and eccentric phases showed an interaction between leg and discipline ($p < 0.001$). Both legs followed a similar pattern with numerous shorter absolute durations in SL than GS, in GS than SG, and in SG than DH, but with a few minor differences between legs (**Figure 5**, **Table 1**). The concentric mode lasted longer on OL than IL for the knee and hip in SL (small effects $d \leq 0.41$), but lasted longer on IL than OL for the knee in GS and SG (medium effects $0.64 \leq d \leq 0.72$), and for the hip in GS (large effect $d = 0.99$) (all $p < 0.001$). The quasi-isometric mode lasted longer on OL than IL for both the knee and hip in GS and SG (all large effects $d \geq 0.90$, except hip in SG medium effect $d = 0.51$), but lasted longer on IL than OL for both the knee and hip in SL (small effects $0.33 \leq d \leq 0.38$) and DH (medium to large effects $0.53 \leq d \leq 1.17$) ($p < 0.006$). The eccentric mode consistently lasted longer on IL than OL for the knee in GS and SG (medium effects $0.69 \leq d \leq 0.75$), and for the hip in GS (medium effect $d = 0.68$), SG (small effect $d = 0.45$), and DH (large effect $d = 1.67$) (**Figure 5**, $p < 0.001$).

Relative Duration of the Concentric, Eccentric, and Quasi-Isometric Phases

The relative concentric, quasi-isometric and eccentric durations in percent of the turn showed an interaction between leg and discipline ($p < 0.001$, **Table 1**). The relative proportion of knee concentric activity was higher in SL than GS and in GS than SG on both OL (medium to large effects $0.59 \leq d \leq 1.61$) and IL (small to medium effects $0.32 \leq d \leq 0.56$) ($p < 0.019$), but was equivalent in DH than SG (and thus lower to GS, $p = 0.015$, medium effect $d = 0.60$) on IL and equivalent in DH than GS

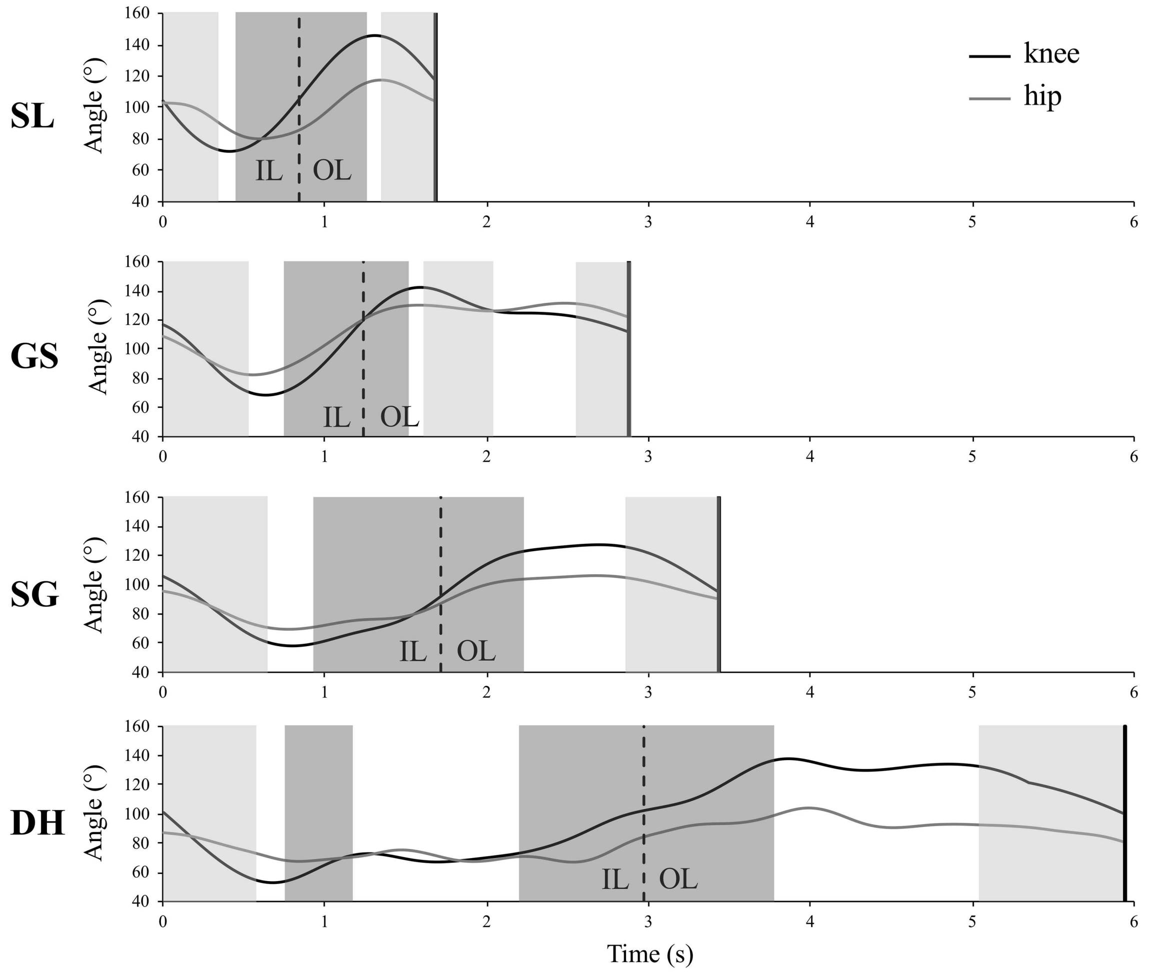

FIGURE 3 | Example of 1 cycle (inside leg, IL and outside leg, OL) for 1 skier-session per discipline expressed in absolute time (s). SL, Slalom; GS, Giant Slalom; SG, Super Giant; DH, Downhill. The gray-shaded areas represent the eccentric (light gray), concentric (dark gray), and quasi-isometric (white background) phases of the knee.

(and thus higher than SG, $p = 0.035$ medium effect $d = 0.52$) on OL. The relative proportion of hip concentric activity was higher in SL than other disciplines on OL ($p < 0.001$, large effects $d > 1.24$), but was higher in GS than other disciplines on IL ($p < 0.021$, small effects vs. SL $d = 0.45$, large effects vs. SG and DH $d > 0.97$) (**Figure 5**, **Table 1**). In addition, the percentage of concentric time was higher on IL than OL for the knee in SG and GS (medium effects $0.58 \leq d \leq 0.61$), and for the hip in GS (large effect $d = 0.94$); but was higher on OL than IL for the knee and hip in SL ($p < 0.017$, medium effects $0.71 \leq d \leq 0.75$, **Figure 5**).

The relative proportion of knee quasi-isometric activity was lower in SL than other disciplines (large effects $d > 1.86$) and lower in GS than SG (medium effect $d = 0.63$) on OL ($p < 0.001$), and was lower in SL and GS (trivial effect $d = 0.06$, $p < 0.001$) and in SG and DH ($p = 0.059$, large effect $d = 0.80$) on the IL. The relative proportion of hip quasi-isometric activity was lower in SL than other disciplines on OL ($p < 0.001$, large effects $d >$ 1.61); but was lower in GS than DH and SG, plus lower in SL than DH on IL ($p < 0.040$, large effects $d > 1.00$) (**Figure 5**, **Table 1**). The percentage of quasi-isometric time was higher on IL than OL for the knee and hip in SL (medium effects $0.64 < d < 0.65$), but was higher on OL than IL for both the knee and hip in GS and SG (all large effects $d \geq 1.08$, except hip in SG small effect $d = 0.33$) ($p < 0.014$, **Figure 5**).

The relative proportion of knee eccentric activity was higher in SL than other disciplines on OL ($p < 0.002$, medium to large effects $d > 0.64$), and lower in DH than other disciplines on IL ($p < 0.024$, large effects $d \geq 0.87$) (**Figure 5**, **Table 1**). The relative proportion of hip eccentric activity was higher in SL than other disciplines on OL ($p < 0.002$, large effects $d \geq 1.02$), without statistical differences between disciplines on IL ($p >$ 0.164, despite large differences between DH vs. GS and SL $d \geq 1.15$) (**Figure 5**, **Table 1**). The percentage of eccentric time was higher on IL than OL for the knee in GS and SG (medium effects $0.70 \leq d \leq 0.78$), and for the hip in GS, SG, and DH

TABLE 1 | Angles related parameters according to Leg and Discipline including a quasi-isometric phase between $\pm 20^{\circ} s^{-1}$.

	Joint		Inside	Leg			Outside	Leg		
			DH	**SG**	**GS**	**SL**	**DH**	**SG**	**GS**	**SL**
Angle (°)	Knee	Min IL/Max OL	58 ± 9^{a}	60 ± 8^{a}	64 ± 9^{a}	67 ± 12^{a}	128 ± 17^{a}	127 ± 8^{a}	132 ± 9^{a}	129 ± 11^{a}
	Hip	Min IL/Max OL	66 ± 3^{a}	70 ± 6^{a}	90 ± 18^{a}	93 ± 21^{a}	89 ± 6^{a}	106 ± 9^{a}	128 ± 18^{a}	126 ± 15^{a}
Mean angular velocity	Knee	Concentric	50 ± 19^{a}	59 ± 16^{ab}	65 ± 16^{b}	63 ± 19^{ab}	52 ± 20^{a}	57 ± 14^{a}	65 ± 19^{a}	$86 \pm 22^{*b}$
		Eccentric	$52 \pm 18^{(*a)}$	$52 \pm 15^{*a}$	$58 \pm 15^{*a}$	72 ± 15^{b}	46 ± 17^{ab}	45 ± 12^{a}	54 ± 16^{b}	$89 \pm 21^{*c}$
	Hip	Concentric	28 ± 5^{a}	36 ± 11^{a}	$43 \pm 14^{*a}$	48 ± 21^{a}	26 ± 4^{ab}	$40 \pm 9^{*ab}$	41 ± 14^{a}	$55 \pm 19^{*b}$
		Eccentric	27 ± 4^{a}	33 ± 8^{a}	$39 \pm 12^{*a}$	38 ± 14^{a}	26 ± 4^{a}	31 ± 7^{a}	34 ± 10^{a}	$42 \pm 14^{*a}$
Absolute duration phase (ms)	Knee	Concentric	$793 \pm 342^{*d}$	$633 \pm 239^{*c}$	$553 \pm 147^{*b}$	375 ± 123^{a}	748 ± 368^{c}	526 ± 195^{b}	458 ± 148^{a}	$426 \pm 81^{*a}$
		Quasi-iso	1042 ± 646^{d}	588 ± 380^{c}	298 ± 219^{b}	$175 \pm 111^{*a}$	919 ± 534^{c}	$858 \pm 354^{*c}$	$506 \pm 263^{*b}$	99 ± 62^{a}
		Eccentric	791 ± 416^{c}	$776 \pm 213^{*c}$	$625 \pm 173^{*b}$	372 ± 126^{a}	726 ± 309^{c}	646 ± 272^{c}	494 ± 206^{b}	367 ± 89^{a}
		Turn duration	$2626 \pm 643^{*d}$	1998 ± 390^{c}	1477 ± 255^{b}	$922 \pm 144^{*a}$	2394 ± 548^{d}	2030 ± 387^{c}	1459 ± 216^{b}	892 ± 134^{a}
	Hip	Concentric	338 ± 293^{ab}	402 ± 191^{b}	$459 \pm 191^{*b}$	248 ± 119^{a}	349 ± 299^{ab}	414 ± 200^{b}	301 ± 181^{a}	$315 \pm 107^{*a}$
		Quasi-iso	$2407 \pm 584^{*d}$	1113 ± 446^{c}	552 ± 364^{b}	$355 \pm 218^{*a}$	2078 ± 423^{d}	$1254 \pm 392^{*c}$	$803 \pm 319^{*b}$	249 ± 172^{a}
		Eccentric	$485 \pm 309^{*ab}$	$500 \pm 229^{*b}$	$468 \pm 218^{*b}$	333 ± 197^{a}	169 ± 199^{a}	414 ± 246^{a}	339 ± 214^{a}	$345 \pm 151^{*a}$
		Turn duration	3230 ± 469^{d}	2015 ± 352^{c}	$1480 \pm 249^{*b}$	$936 \pm 156^{*a}$	$2597 \pm 588^{*d}$	$2083 \pm 38*2^{c}$	1443 ± 200^{b}	909 ± 135^{a}
Relative duration phase (% cycle)	Knee	Concentric	32 ± 15^{a}	$32 \pm 11^{*a}$	$37 \pm 9^{*b}$	41 ± 13^{c}	31 ± 14^{b}	26 ± 9^{a}	32 ± 11^{b}	$48 \pm 7^{*c}$
		Quasi-iso	38 ± 21^{b}	28 ± 15^{b}	20 ± 13^{a}	$19 \pm 11^{*a}$	38 ± 18^{bc}	$42 \pm 15^{*c}$	$34 \pm 16^{*b}$	11 ± 5^{a}
		Eccentric	30 ± 14^{a}	$40 \pm 11^{*b}$	$43 \pm 11^{*b}$	40 ± 12^{b}	31 ± 14^{a}	32 ± 13^{a}	34 ± 14^{a}	41 ± 8^{b}
	Hip	Concentric	10 ± 8^{a}	20 ± 11^{ab}	$31 \pm 12^{*c}$	26 ± 12^{b}	12 ± 9^{a}	20 ± 9^{a}	21 ± 12^{a}	$35 \pm 11^{*b}$
		Quasi-iso	74 ± 12^{c}	54 ± 16^{bc}	37 ± 22^{a}	$39 \pm 24^{*ab}$	81 ± 13^{b}	$60 \pm 15^{*b}$	$55 \pm 20^{*b}$	27 ± 17^{a}
		Eccentric	$16 \pm 10^{*a}$	$25 \pm 12^{*a}$	$32 \pm 15^{*a}$	35 ± 20^{a}	6 ± 7^{a}	20 ± 12^{a}	24 ± 15^{a}	$38 \pm 16^{*b}$

SL, Slalom; GS, Giant Slalom; SG, Super Giant; DH, Downhill. Quasi-iso: quasi-isometric phase. Superscript letters represent post-hoc pairwise comparisons between disciplines with two disciplines with the same letters being not statistically different and a<b<c<d (mean increasing order) at $p < 0.05$. [*]Inside Leg different from Outside Leg in a given discipline, while indicating the higher value. (*) indicates a trend with $p < 0.10$. Nb: Turn duration is different for Knee and Hip due to a different sample size (see Methods for details).

(small to medium effects $0.39 \leq d \leq 0.69$); but was higher on OL than IL for the hip in SL ($p < 0.028$, small effect $d = 0.21$) (**Figure 5**).

DISCUSSION

This study is novel and aimed to examine the knee and hip kinematics in ecologically valid skiing conditions by measuring these parameters with a portative wireless technology during the four Olympic alpine ski disciplines. In accordance with our hypothesis, the current results displayed statistical differences in joint kinematic characteristics according discipline and leg in elite skiers. Specifically, our results showed the importance of the quasi-isometric contraction mode on OL for both the knee (38, 42, 34, 11% in DH, SG, GS, and SL, respectively) and the hip (81, 60, 55, 27% in DH, SG, GS, and SL, respectively) although it was not traditionally taken into account in previous alpine skiing kinematic analysis. All disciplines with the exception of DH showed an asymmetrical behavior of the knee contraction phase durations according to their inside or outside status during the ski turn ($p < 0.05$, **Figure 5**). Contrary to the traditional classification into technical (SL and GS) and speed disciplines (SG and GH) and to our secondary hypothesis, the present results showed that GS and SG present similarities in their articular kinematic pattern (**Figure 5**) which was significantly different to both SL and DH.

Importance of the Quasi-Isometric Phase

We observed greater knee amplitude (64–132°) in GS compared with a pioneer study (66–114°) (Berg et al., 1995) due to greater knee extension on OL (+18° of knee extension). This is likely due to a greater edge set and body inclination in the turn with the modern technique of carving with shaped skis. Knee joint angles have been related to race performance in SL with larger knee angles in the outside posture for the best skiers (Pozzo et al., 2010). Indeed, it was suggested that having these knee angular extensions at the minimum radius can account for a better modulation of the force demands derived from the external forces during the turn (Pozzo et al., 2010). The IL showed more similarities with pioneer studies as the knee angle reached a minimum of 64° (vs. 66° in Berg et al., 1995).

Hip maximum angles tended to be lower in speed than technical disciplines ($p < 0.090$) suggesting the maintenance of a tuck position without trunk extension phases. Indeed, postures that minimize the exposed frontal area of a skier are a key factor to reduce aerodynamic drag, thereby elevating velocity and reducing overall run time (Supej and Holmberg, 2019). Aerodynamic drag becomes more important as the speed increases (e.g., from SL to DH) (Gilgien et al., 2018a), whereas ski-snow friction is relatively more important at slower speeds, particularly when turning, as the ski-snow friction dissipates most of the energy during SL and GS (Supej et al., 2013). However, guiding the skis smoothly remains the priority in the speed events (Supej and Holmberg, 2019). The current results

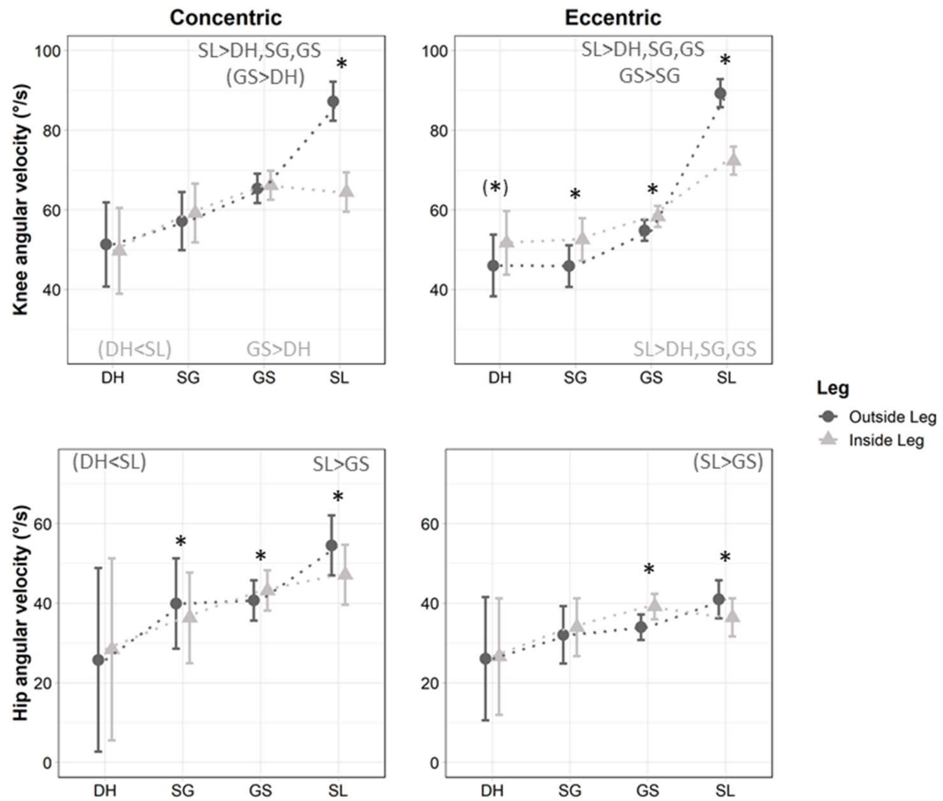

FIGURE 4 | Mean concentric and eccentric angular velocity (±20°.s^{-1}) for the right knee (KR) and hip (HR) during Downhill (DH), Super Giant (SG), Giant Slalom (GS), and Slalom (SL) when separated into concentric, eccentric, and quasi-isometric modes. *denotes a significant difference between inside (light gray and triangles) and outside leg (dark gray and plain circles). < or > differences between disciplines for the inside (light gray) or the outside (dark gray) leg. $p < 0.05$, ( ) indicates a trend with $p < 0.10$.

suggest that this smooth steering is executed in the aerodynamic tuck position as characterized by small hip angles (**Table 1**).

However, more than the extreme angular positions which were rather similar between the disciplines, the angular velocities, and/or duration of the contraction modes may be more discriminant. Indeed, the functional phase durations (IL/OL) were increasingly shorter from DH to SG, to GS and then to SL leading to faster muscle contractions for both the eccentric and concentric modes (**Table 1**). A kinetic study has previously shown that this shorter duration in SL did not affect the maximum ground reaction force (∼3.15 body weight) but decreased the mean total ground reaction force as compared to GS (Kröll et al., 2015b). Moreover, the shorter SL turns decreased the time available for independent leg action, leading to a more balanced distribution between the two legs with synchronous legs loading in SL (Kröll et al., 2015b).

In order to compare the present results to those of Berg and Eiken (1999), we extracted angle data from the figures using Web Plot Digitizer (Rohatgi, 2015) and computed the angular velocities. These reconstructed angular velocity values (mean concentric/eccentric knee angular velocities of 32/-28°.s^{-1}, 46/-34°.s^{-1}, and 56/-57°.s^{-1} in SG, GS, and SL, respectively) were in accordance with an increasing velocity from SG to SL observed in the present study. However, a higher mean eccentric contraction velocity was observed on OL, mainly for the technical disciplines in the present study compared to a traditional analysis of our data (**Table 2**). Considerable changes in ski racing during the past decades (carving skis, skier's velocity) probably account for this angular velocity increase. The reconstructed (see above, Rohatgi, 2015) angular velocity curve from Kröll et al. (2015a,b) suggest a mean angular velocity across the whole ski cycle for concentric/eccentric modes close to the present data [47/-44°.s^{-1} (Kröll et al., 2015a) and 42/-47°.s^{-1} (Kröll et al., 2015b)] (**Table 2**). However, by averaging the angular velocity in the same manner as traditional ski research, quasi-isometric contractions were not taken into consideration. This could lead to (i) overlooking a key component of the speed disciplines; and (ii) underestimation of the mean velocity during dynamic contractions (**Table 1**). As such, we proposed to separate the angular velocities with a threshold of ±20°.s^{-1} to identify a quasi-isometric phase. Such characterization showed a quasi-isometric component that significantly depended on discipline with an interaction of the leg (**Figure 5**). For example, SL had a significantly lower amount of time spent in quasi-isometric than all other disciplines on OL knee and hip, suggesting a highly dynamic style.

TABLE 2 | Angles related parameters according to Leg and Discipline analyzed with Berg et al. (1995) cycle partition in eccentric/concentric phases.

			Inside	Leg			Outside	Leg		
			DH	**SG**	**GS**	**SL**	**DH**	**SG**	**GS**	**SL**
Max angular velocity ($^{\circ}.s^{-1}$)	Knee	Concentric	80 ± 40^{a}	94 ± 25^{a}	98 ± 26^{a}	98 ± 30^{a}	85 ± 37^{a}	96 ± 25^{a}	97 ± 30^{a}	$116 \pm 32^{*b}$
		Eccentric	75 ± 33^{a}	$74 \pm 23^{*a}$	$82 \pm 22^{*a}$	117 ± 27^{b}	69 ± 32^{a}	69 ± 22^{a}	79 ± 25^{a}	$124 \pm 30^{*b}$
	Hip	Concentric	32 ± 12^{a}	50 ± 18^{a}	$58 \pm 24^{*a}$	66 ± 33^{a}	28 ± 9^{a}	$55 \pm 17^{(*a)}$	54 ± 24^{a}	$72 \pm 31^{*a}$
		Eccentric	29 ± 9^{a}	$42 \pm 14^{(*a)}$	$49 \pm 21^{*a}$	47 ± 23^{a}	21 ± 9^{a}	37 ± 14^{a}	40 ± 18^{a}	$50 \pm 21^{*a}$
Mean angular velocity ($^{\circ}.s^{-1}$)	Knee	Concentric	36 ± 18^{a}	$45 \pm 16^{*ab}$	$55 \pm 17^{*c}$	54 ± 19^{bc}	39 ± 19^{ab}	36 ± 11^{a}	48 ± 19^{b}	$79 \pm 22^{*c}$
		Eccentric	37 ± 16^{a}	$42 \pm 15^{*a}$	$49 \pm 16^{*b}$	61 ± 16^{c}	33 ± 16^{ab}	32 ± 12^{a}	40 ± 16^{b}	$80 \pm 22^{*c}$
	Hip	Concentric	13 ± 4^{a}	21 ± 8^{a}	33 ± 15^{a}	37 ± 22^{a}	14 ± 4^{a}	22 ± 7^{a}	25 ± 13^{a}	45 ± 19^{b}
		Eccentric	14 ± 5^{a}	$22 \pm 8^{*a}$	$30 \pm 14^{*a}$	28 ± 15^{a}	11 ± 4^{a}	18 ± 7^{a}	21 ± 10^{a}	$33 \pm 15^{*b}$
Absolute duration phase (ms)	Knee	Concentric	$1321 \pm 399^{*d}$	905 ± 284^{c}	697 ± 178^{b}	465 ± 125^{a}	1183 ± 453^{d}	$943 \pm 277^{*c}$	700 ± 224^{b}	476 ± 92^{a}
		Eccentric	$1304 \pm 493^{(*d)}$	1093 ± 288^{c}	$779 \pm 182^{*b}$	$457 \pm 140^{*a}$	1210 ± 381^{d}	1087 ± 320^{c}	758 ± 250^{b}	416 ± 93^{a}
	Hip	Concentric	$1539 \pm 485^{*d}$	939 ± 278^{c}	$724 \pm 202^{*b}$	378 ± 133^{a}	1341 ± 302^{d}	$1015 \pm 278^{*c}$	676 ± 265^{b}	$413 \pm 118^{*a}$
		Eccentric	$1690 \pm 245^{*d}$	1076 ± 292^{c}	755 ± 180^{b}	$558 \pm 156^{*a}$	1256 ± 422^{d}	1067 ± 373^{c}	767 ± 258^{b}	495 ± 141^{a}
Relative duration phase (% cycle)	Knee	Concentric	51 ± 12^{a}	45 ± 11^{a}	47 ± 8^{a}	51 ± 12^{a}	49 ± 14^{ab}	47 ± 12^{a}	$48 \pm 14^{*a}$	$53 \pm 7^{*b}$
		Eccentric	49 ± 12^{ab}	55 ± 11^{b}	$53 \pm 8^{*ab}$	$49 \pm 12^{*a}$	51 ± 14^{ab}	53 ± 12^{b}	52 ± 14^{b}	47 ± 7^{a}
	Hip	Concentric	47 ± 10^{ab}	47 ± 12^{b}	$49 \pm 10^{*b}$	41 ± 14^{a}	52 ± 8^{a}	49 ± 13^{a}	47 ± 17^{a}	$46 \pm 12^{*a}$
		Eccentric	53 ± 10^{ab}	53 ± 12^{a}	51 ± 10^{a}	$59 \pm 14^{*b}$	48 ± 8^{a}	51 ± 13^{a}	$53 \pm 17^{*a}$	54 ± 12^{a}

*SL, Slalom; GS, Giant Slalom; SG, Super Giant; DH, Downhill. Superscript letters represent post-hoc pairwise comparisons between disciplines with two disciplines with the same letters being not statistically different and $a<b<c<d$ (mean increasing order) at $p < 0.05$. *Inside Leg different from Outside Leg in a given discipline, while indicating the higher value. (*) indicates a trend with $p < 0.10$.*

Nevertheless, one should keep in mind that these velocities are rather slow compared to values previously reported in running (Struzik et al., 2016) or team sports (Ball, 2008) with knee angular velocity reaching ~1,000°.s^{-1} to ~1,500°.s^{-1} respectively (**Figure 4**). This difference can be attributed to the fact that both feet are in contact with the ground in alpine skiing whereas most sports alternate right/left ground contact with (e.g., running) or without (e.g., walking) a suspension phase. As such, alpine skiing doesn't theoretically allow for open chain movements except during jumps or micro-movements due to vibrations. Alpine skiing is thus characterized by slow dynamic motions at high loads even on IL (Meyer et al., 2019) rather than pure isometric efforts. Albeit one could argue that those velocities remain relatively close to the quasi-isometric mode as compared to other sports, it is important to acknowledge than even small differences in velocities have important neuromuscular consequences. For example, two slow angular velocities (30 and 90°.s^{-1}) led to different fatigue characteristics (Morel et al., 2019). As such, dry-land training should match the angular velocities and contraction times reported in the current study per discipline.

Inside and Outside Leg Specificities Among Alpine Skiing Disciplines

Racers have always known that the best functional technique in skiing is based on using their legs independently (LeMaster, 2010). The current data reinforce the need to analyze each leg separately. In the current study, mean knee angular velocities for the knee were higher with large effects on OL than IL in SL both eccentrically and concentrically. However, the reverse pattern was seen in GS and SG with higher mean angular eccentric velocities (small effects) for the knee on IL than OL (**Table 1**). Thus, all disciplines except for DH showed an asymmetrical behavior of the legs according to their inside or outside status during the ski turn. Using pressure insoles, it has previously been reported a load of ~2 body weight on OL and ~0.75 body weight on IL in GS (Kröll et al., 2015b). This suggests that the load on IL remains substantial, especially considering the flexed knee angles. Moreover, the extended OL may benefit from more skeletal support, while the flexed IL requires more muscular support (Hintermeister et al., 1997), and the muscle activity required to stabilize the flexed leg may therefore approach that of the extended leg, even if the latter is supporting greater force in GS (Falda-Buscaiot et al., 2017; Meyer et al., 2019). Taken together, these results suggest the importance of training at the closed knee angles observed on IL (**Table 1**, **Figure 5**). Both legs work independently during the turn with a more extended OL to resist the pressure and an IL more bent due to inclination. During the subsequent transition phase, both legs reached the same position. Thus, the outside knee was more extended during the turning phase than at the turn switch where the skis slide flat without pressure.

Mean hip angular velocities were higher on OL than IL in SL both eccentrically (small effect) and concentrically (medium effect). A reverse pattern was also seen in GS with higher values on IL than OL. No asymmetry was observed in DH and SG, except concentrically in SG where a higher mean angular velocity was seen on OL than IL (small effect). Thus, the hip displayed an asymmetrical pattern in the technical disciplines, almost no asymmetry in SG and a marked symmetry in DH (**Figure 4**).

In SG and GS, more relative time was spent in concentric and eccentric modes for the knee on IL than OL (medium

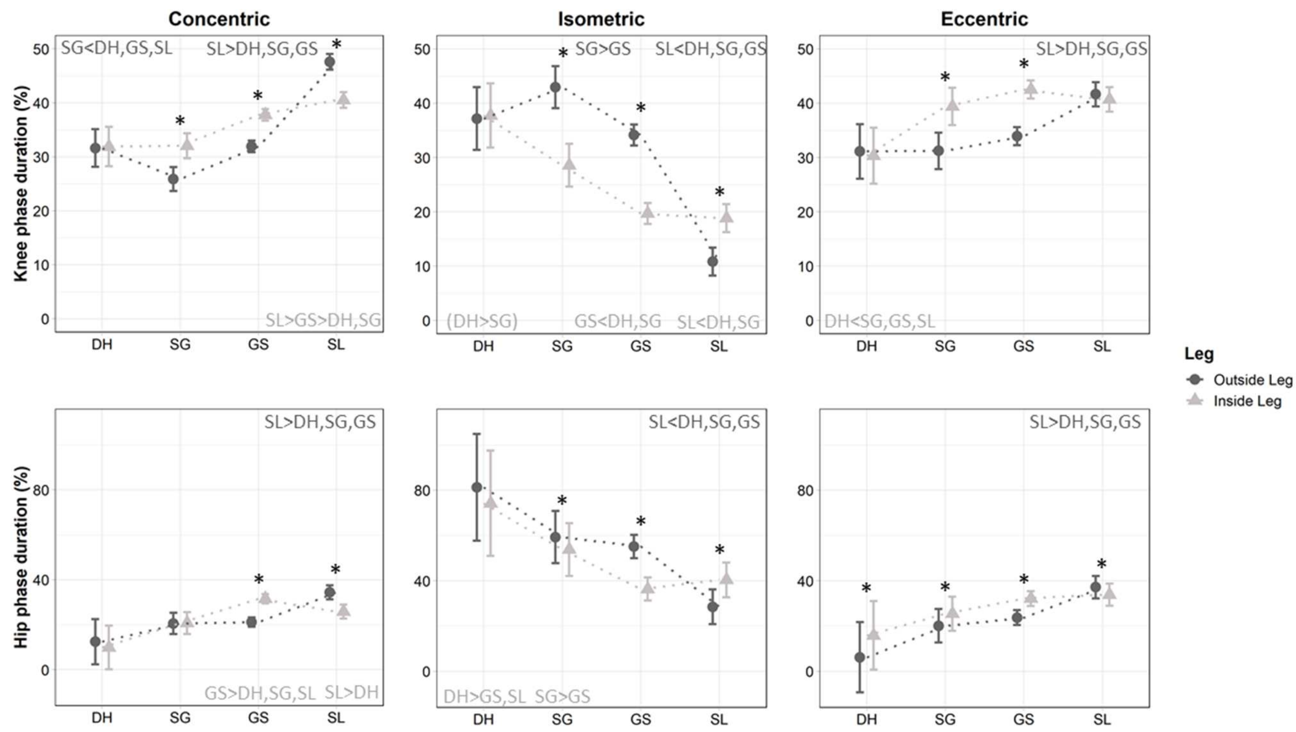

FIGURE 5 | Relative duration of the eccentric, quasi-isometric and concentric phases for the knee and hip during Downhill (DH), Super Giant (SG), Giant Slalom (GS), and Slalom (SL) for the outside and inside leg. * denotes a significant difference between inside (light gray and triangles) and outside leg (dark gray and plain circles). < or > differences between disciplines for the inside (light gray) or the outside (dark gray) leg. $p < 0.05$, ( ) indicates a trend with $p < 0.10$.

effects), meaning that in the open angles, less time was spent in concentric and eccentric modes to the benefit of quasi-isometric mode (**Figure 5**). The IL (closed knee angles) showed a more dynamic style than OL (open angles) which displayed a more marked quasi-isometric component. Contrary to DH and SL, quasi-isometric mode was markedly prevalent in GS and SG on OL (GS 34% and SG 42%, **Figure 5**). Moreover, this marked quasi-isometric OL seems to be also isotonic as suggested by the observations from Meyer et al. (2019) showing that maximal vertical forces ($\sim$12 N.kg^{-1}) were attained at 30% of the turn and were thereafter maintained until 70% of the cycle in GS. The opposite pattern was seen in SL as quasi-isometric mode was more marked on IL compared with OL (medium effects), albeit occupying only 19% of relative time on IL vs. $\sim$40% in eccentric and concentric modes. The DH showed a balanced pattern without any bilateral difference, and a predominance of quasi-isometric mode at the knee (38% on both IL and OL) and hip joint (74% on IL, 81% on OL). The hip works more eccentrically on IL than OL in DH/SG/GS (small to medium effects), while SL displayed a reverse pattern (small effect). In SL, we could speculate that the OL must come back quicker than the IL to start the new turn. Albeit the practical significance of the asymmetries of knee angular behavior in ski training remains to be elucidated, the present data propose new viewpoints on the outside and inside leg specificities.

Questioning of the Traditional Technical/Speed Disciplines Classification

Interestingly, the traditional partition between technical and speed disciplines may be questioned as GS and SG presented similarities (**Figure 2**), showing both a significantly faster knee eccentric mean angular velocity on IL than OL (small effects) whereas SL showed an opposite pattern (large effect). They also showed a longer quasi-isometric phase on OL than IL (large effects, **Figure 5**). This suggests that polyvalent skiers practicing GS and SG may develop a common and even opposite pattern to Slalomers. Thus, a new group pooling SG and GS emerged from the present analysis. DH showed symmetrical technical features (mean angular velocities, time spent in quasi-isometric/eccentric/concentric modes) whereas SG/GS were clearly asymmetrical. SL was also asymmetrical with the inverse pattern than SG/GS group. We could speculate that the "polyvalent" skiers practicing GS and SG may present some similarities in their muscular properties. These results challenged the traditional partition of the speed (DH/SG) and technical (SL/GS) disciplines, giving a rationale for the polyvalent group including GS and SG that was previously created at the French Ski Federation. Whether the inside and outside leg specificities are related to the performance of the athletes remains to be elucidated as well as the facility to switch from a profile to another.

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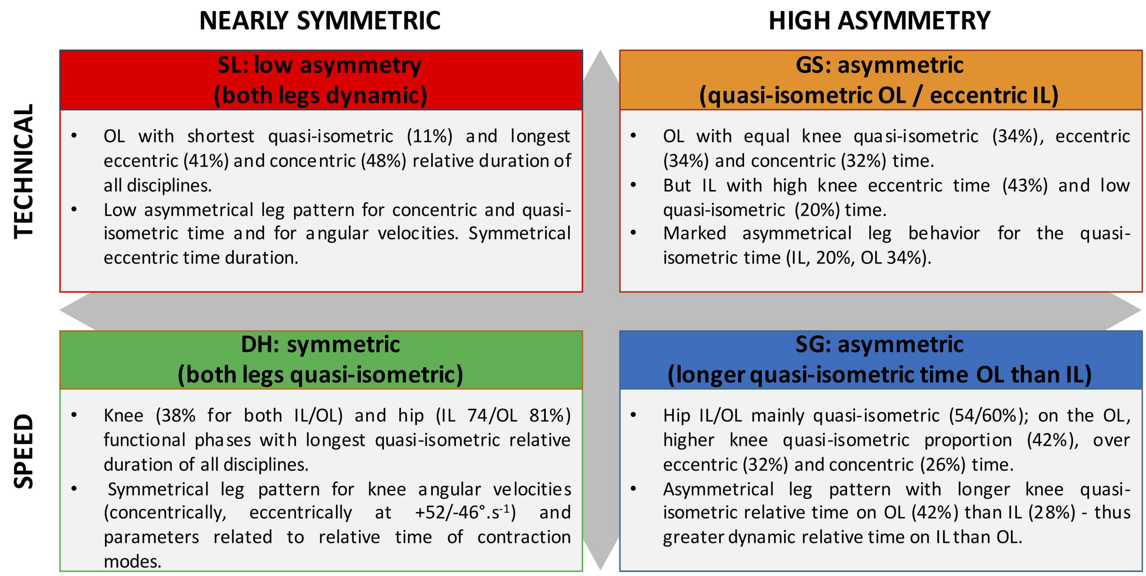

FIGURE 6 | Synthetic overview of four alpine skiing disciplines based on joint kinematic characteristics (knee/hip angular velocity and position).

Interest of 2D Density Plots Visualization and Synthetic Overview

The 2D density plots (**Figure 2**) are proposed as an original qualitative method for data visualization to illustrate the statistical results discussed above that may be used by physicians and coaches. For example, we could see that SL displayed a predominance of slow concentric and quasi-isometric speeds on IL but a more dynamic distribution on OL with prevalent concentric and eccentric speeds (at $\pm\sim 150^{\circ}.s^{-1}$). SL seems to be the most complete discipline because of the broader range of angular velocities and knee angles in use whereas on the opposite side DH required extremely low speed/quasi-isometric mode on both legs. As discussed above, SG and GS showed similarities. In GS, the time spent in quasi-isometric mode on OL ($\sim 130^{\circ}$) was highly prevalent. In SG, there was two prevalent zones corresponding to the quasi-isometric mode both on OL ($\sim 120^{\circ}$) and IL ($\sim 60^{\circ}$). There is an inherent variability in alpine skiing in the knee angular position (Pozzo et al., 2010), higher than variability seen in cycling or running for joint angles, cycle-to-cycle duration, and stride time (Padulo et al., 2012; Connick and Li, 2015). The 2D plot representation may be generalized to other sports to summarize various characteristic patterns and their variability.

Methodological Considerations

For the practical applications, it was assumed that the knee angular velocity reflects indirectly the muscle shortening/lengthening velocity. However, the macroscopic "quasi-isometric," "concentric," and "eccentric" modes seen at the knee and hip articulations levels may not be representative of the contractile aspects at the muscle level (real fascicule length and shortening velocity) (Fukunaga et al., 1997; Hauraix et al., 2013). Indeed, even if the angular velocity of knee extension is kept constant, the shortening velocity of a fascicle is dependent on the force applied to the muscle-tendon complex (Ichinose et al., 2000). Additionally, the muscle-tendon interactions complicate the interpretation of simple movements (Ishikawa et al., 2005). For example, during walking, the joint indicated an eccentric contraction mode whereas the "*in vivo*" mode was isometric (Fukunaga et al., 2001). Nevertheless, we believe that this approach may be simple and useful for strength and conditioning coaches to implement specific exercises.

Previous studies have often zoomed on a restrained number of gates and runs, limiting the generalizability of their results to alpine ski racing. However, we selected a large number of run and cycles across trials and course designs to provide a true representation of the knee and hip joint kinematics and their variability in skiers. Importantly, the study used miniaturized wireless sensors to avoid any disturbance from real ski training (e.g., no backpack) and be representative of elite alpine ski racing.

It should be acknowledged that the filtering choice may have hindered differences between SL and the other disciplines due to an average underestimation of 8% in the signal amplitude. Indeed, edge's effects were unavoidable as the signal of interest was very close to the noise despite the very selective filter. However, despite the high constraints of the environment, the filter characteristics gave good results and represented an acceptable compromise of signal processing for this dataset (**Figure 1**).

It must be recognized that the intra-run (i.e., cycles) and inter-runs variability was taken into account by the factor "skier-session" for which a random effect was applied. However, the global variability of the skier-session (subject and course setting of the day) does not allow to separate the variability due to the skier alone, the day of testing alone (course setting, slope conditions), or the run/cycle number. As such, including the turn number within the analyses would provide an additional layer of information. However, this information would also be dependent of external (e.g., slope, snow conditions) and internal (e.g., fatigue) confounding factors. Therefore, as the aim of the current project was to provide a description of an "average" cycle, we did not want to separate the variability inherent to alpine ski racing (intra/inter runs) in this experiment.

Lastly, it should be acknowledged that some differences were statistically significant due to the very large amount of data but may not be functionally relevant due to their relatively small magnitude ($\sim$3–5°.s^{-1}) with large SD. However, it should be mentioned that experienced skiers displayed a high degree of stability in their kinematic parameters despite the variability encountered on the slope in ski training as supported by a previous study showing a preserved posture in advanced skiers compared with beginners (Akutsu et al., 2008; Kiryu et al., 2011). Therefore, very small angle variations in the context of high-performance training may be meaningful.

Perspectives

The present study characterized the knee and hip kinematic specificities of the alpine skiing Olympic disciplines. A synthetic overview is provided to help coaches to adapt their training to the features of each discipline (**Figure 6**). Especially, the quasi-isometric mode, evidenced as a key component of alpine skiing, which is known to generate training adaptations (Lum and Barbosa, 2019) that are joint angle-specific, especially through central (i.e., neural) pathways (Noorkõiv et al., 2014). Thus, it seems important to consider relative and absolute time as well as the specific angles at which the quasi-isometric mode occurs for each discipline during conditioning training.

Moreover, eccentric activity duration of the quadriceps muscle represents 30 to 43% on each leg, which is considered to be a unique feature of alpine skiing (Berg et al., 1995). Since eccentric muscle contractions require different activation strategies and programming processes by the central nervous system (Fang et al., 2004), regular application of eccentric exercise training is also warranted for alpine skiers. Of note, in alpine skiers, eccentric cycling training increased isometric torque only at greater quadriceps length probably due to sarcomerogenesis (Gross et al., 2010), As discipline-specific muscle adaptations depending on joint angle and contraction modes have been suggested in alpine skiers (Lešnik et al., 2012; Alhammoud et al., 2019), the present results may be used to adapt the training contents accordingly. Practically, the current results suggest that dryland strength and conditioning sessions should focus on slow movements at the specific angles of the OL and IL. It should however be acknowledged that the skiers are exposed to high frequency vibrations superimposed to the movement pattern (**Figure 1**), and that a loss of control may require a quick repositioning. As such, the slow velocity training should be completed with rapid force development (Jordan et al., 2015).

CONCLUSION

This study examined the impact of skiing discipline and leg (outside/inside) on knee and hip angle-related parameters during real on-hill training. The continuous recording performed in this unique project in elite alpine skiers allowed us to characterize the presence of concentric, quasi-isometric and eccentric actions. The proportion of those phases significantly depended on the discipline in interaction with the inside/outside leg. The results showed a lower knee quasi-isometric duration on OL in SL than other disciplines, suggesting a highly dynamic style. Quasi-isometric mode was significantly longer on OL than IL in GS and SG but was significantly longer on IL than OL in SL. Thus, GS and SG showed similarities, with a significantly faster knee eccentric mean angular velocity on IL than OL whereas SL showed an opposite pattern. These considerations may be used to train the open and closed angles with specific contraction modes and exercises. Moreover, the "polyvalent" skiers practicing GS and SG may present some similarities in their muscular properties, challenging the traditional partition of the speed (DH/SG) and technical (SL/GS) disciplines.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, upon reasonable request, to any qualified researcher.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Inter-University Laboratory of Human Movement Biology. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MA, CHau, and BM designed the study. MA collected the data. MA, CHan, FM, CHau, and BM analyzed the data and drafted the manuscript. All authors revised and approved the manuscript.

ACKNOWLEDGMENTS

The authors thank the Skiers for their participation and the Head coaches. The authors thank Paul James Read for proofreading.

REFERENCES

Akutsu, T., Kiryu, T., Ushiyama, Y., and Murayama, T. (2008). Evaluation of functional activities during skiing exercise by knee joint angles and surface EMG signals. *Trans. Soc. Instrum. Control Eng.* 44, 905–910. doi: 10.9746/ve.sicetr1965.44.905

Alhammoud, M., Morel, B., Hansen, C., Wilson, M., Mecca, R., Nael, E., et al. (2019). Discipline and sex differences in angle-specific isokinetic analysis in elite skiers. *Int. J. Sports Med.* 40, 317–330. doi: 10.1055/a-0850-0016

Ball, K. (2008). Biomechanical considerations of distance kicking in Australian rules football. *Sports Biomech.* 7, 10–23. doi: 10.1080/14763140701683015

Berg, H. E., and Eiken, O. (1999). Muscle control in elite alpine skiing. *Med. Sci. Sports Exerc.* 31, 1065–1067.

Berg, H. E., Eiken, O., and Tesch, P. A. (1995). Involvement of eccentric muscle actions in giant slalom racing. *Med. Sci. Sports Exerc.* 27, 1666–1670.

Brysbaert, M., and Stevens, M. (2018). Power analysis and effect size in mixed effects models: a tutorial. *J. Cogn.* 1:9. doi: 10.5334/joc.10

Cnaan, A., Laird, N. M., and Slasor, P. (1997). Using the general linear mixed model to analyse unbalanced repeated measures and longitudinal data. *Stat. Med.* 16, 2349–2380. doi: 10.1002/(sici)1097-0258(19971030)16:20<2349::aid-sim667>3.0.co;2-e

Connick, M. J., and Li, F.-X. (2015). Prolonged cycling alters stride time variability and kinematics of a post-cycle transition run in triathletes. *J. Electromyogr. Kinesiol.* 25, 34–39. doi: 10.1016/j.jelekin.2014.08.009

Falda-Buscaiot, T., Hintzy, F., Rougier, P., Lacouture, P., and Coulmy, N. (2017). Influence of slope steepness, foot position and turn phase on plantar pressure distribution during giant slalom alpine ski racing. *PLoS ONE* 12:e0176975. doi: 10.1371/journal.pone.0176975

Fang, Y., Siemionow, V., Sahgal, V., Xiong, F., and Yue, G. H. (2004). Distinct brain activation patterns for human maximal voluntary eccentric and concentric muscle actions. *Brain Res.* 1023, 200–212. doi: 10.1016/j.brainres.2004.07.035

Fasel, B., Spörri, J., Gilgien, M., Gerber, N., Falbriard, M., and Müller, E. (2016). "IMU and GNSS-based turn switch detection in alpine ski racing," in *Science and Skiing VII,* eds E. Müller, J. Kröll, S. Lindinger, J. Pfusterschmied, and T. Stöggl (Aachen: Meyer and Meyer Sport), 86–92.

Federolf, P., von Tscharner, V., Haeufle, D., Nigg, B., Gimpl, M., and Müller, E. (2009). "Vibration exposure in alpine skiing and consequences for muscle activation levels," in *Science and Skiing IV,* eds E. Müller, S. Lindinger, and T. Stöggl (Maidenhead: Meyer and Meyer Verlag), 19–25.

Fukunaga, T., Ichinose, Y., Ito, M., Kawakami, Y., and Fukashiro, S. (1997). Determination of fascicle length and pennation in a contracting human muscle *in vivo*. *J. Appl. Physiol.* 82, 354–358. doi: 10.1152/jappl.1997.82.1.354

Fukunaga, T., Kubo, K., Kawakami, Y., Fukashiro, S., Kanehisa, H., and Maganaris, C. N. (2001). *In vivo* behaviour of human muscle tendon during walking. *Proc. Biol. Sci.* 268, 229–233. doi: 10.1098/rspb.2000.1361

Gilgien, M., Kröll, J., Spörri, J., Crivelli, P., and Müller, E. (2018a). Application of dGNSS in alpine ski racing: basis for evaluating physical demands and safety. *Front. Physiol.* 9:145. doi: 10.3389/fphys.2018.00145

Gilgien, M., Reid, R., Raschner, C., Supej, M., and Holmberg, H.-C. (2018b). The training of olympic alpine ski racers. *Front. Physiol.* 9:1772. doi: 10.3389/fphys.2018.01772

Gross, M., Lüthy, F., Kroell, J., Müller, E., Hoppeler, H., and Vogt, M. (2010). Effects of eccentric cycle ergometry in alpine skiers. *Int. J. Sports Med.* 31, 572–576. doi: 10.1055/s-0030-1254082

Hauraix, H., Nordez, A., and Dorel, S. (2013). Shortening behavior of the different components of muscle-tendon unit during isokinetic plantar flexions. *J. Appl. Physiol.* 115, 1015–1024. doi: 10.1152/japplphysiol.00247.2013

Hawkins, D., and Hull, M. L. (1990). A method for determining lower extremity muscle-tendon lengths during flexion/extension movements. *J. Biomech.* 23, 487–494. doi: 10.1016/0021-9290(90)90304-l

Higbie, E. J., Cureton, K. J., Warren, G. L., and Prior, B. M. (1996). Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. *J. Appl. Physiol.* 81, 2173–2181. doi: 10.1152/jappl.1996.81.5.2173

Hintermeister, R. A., Lange, G. W., O'Connor, D. D., Dillman, C. J., and Steadman, J. R. (1997). "Muscle activity of the inside and outside leg in slalom and giant-slalom skiing," in *Science and Skiing,* eds E. Müller, H. Schwameder, E. Kornexl, and C. Raschner (London: Taylor and Francis), 141–149.

Hintermeister, R. A., O'Connor, D. D., Dillman, C. J., Suplizio, C. L., Lange, G. W., and Steadman, J. R. (1995). Muscle activity in slalom and giant slalom skiing. *Med. Sci. Sports Exerc.* 27, 315–322.

Ichinose, Y., Kawakami, Y., Ito, M., Kanehisa, H., and Fukunaga, T. (2000). *In vivo* estimation of contraction velocity of human vastus lateralis muscle during "isokinetic" action. *J. Appl. Physiol.* 88, 851–856. doi: 10.1152/jappl.2000.88.3.851

Ishikawa, M., Komi, P. V., Grey, M. J., Lepola, V., and Bruggemann, G.-P. (2005). Muscle-tendon interaction and elastic energy usage in human walking. *J. Appl. Physiol.* 99, 603–608. doi: 10.1152/japplphysiol.00189.2005

Jordan, M. J., Aagaard, P., and Herzog, W. (2015). Rapid hamstrings/quadriceps strength in ACL-reconstructed elite alpine ski racers. *Med. Sci. Sports Exerc.* 47, 109–119. doi: 10.1249/MSS.0000000000000375

Kiryu, T., Murayama, T., and Ushiyama, Y. (2011). Influence of muscular fatigue on skiing performance during parallel turns. *Conf. Proc. IEEE Eng. Med. Biol. Soc.* 2011, 8187–8190. doi: 10.1109/IEMBS.2011.6092019

Kröll, J., Schiefermüller, C., Birklbauer, J., and Müller, E. (2005). "Inline-skating as a dry land modality for slalom racers-electromyographic and dynamic similarities and differences," in *Science and Skiing III,* eds. E. Mueller, S. Lindinger, and T. Stoeggl (Maidenhead: Meyer and Meyer Sport), 76–87.

Kröll, J., Spörri, J., Fasel, B., Müller, E., and Schwameder, H. (2015a). "Type of muscle control in elite alpine skiing – is it still the same than in 1995?," in *Science and Skiing VI,* eds E. Müller, J. Kröll, S. Lindinger, J. Pfusterschmied, and T. Stöggl (Aachen: Meyer and Meyer Sport), 56–64.

Kröll, J., Spörri, J., Kandler, C., Fasel, B., Müller, E., and Schwameder, H. (2015b). "Kinetic and kinematic comparison of alpine ski racing disciplines as a base for specific conditioning regimes," in *ISBS-Conference Proceedings Archive,* eds F. Colloud, M. Domalain and T. Monnet (Poitiers), 33.

Kröll, J., Wakeling, J. M., Seifert, J. G., and Müller, E. (2010). Quadriceps muscle function during recreational alpine skiing. *Med. Sci. Sports Exerc.* 42, 1545–1556. doi: 10.1249/MSS.0b013e3181d299cf

Kuznetsova, A., Brockhoff, P. B., and Christensen, R. H. B. (2017). lmerTest package: tests in linear mixed effects models. *J. Stat. Softw.* 82, 1–26. doi: 10.18637/jss.v082.i13

LeMaster, R. (2010). *Ultimate Skiing*. Champaign, IL: Human Kinetics.

Lenth, R. (2019). *Data From: emmeans: Estimated Marginal Means aka Least-Squares Means*. R package version 1.4. Available online at: https://CRAN.R-project.org/package=emmeans

Lešnik, B., Šimuniþ, B., Žvan, M., and Pišot, R. (2012). "Adaptation of vastii muscles in top skiers from different alpine skiing disciplines," in *Science and Skiing V,* eds E. Müller, S. Lindinger, T. Stöggl (Maidenhead: Meyer and Meyer Sport), 251–262.

Lum, D., and Barbosa, T. M. (2019). Brief review: effects of isometric strength training on strength and dynamic performance. *Int. J. Sports Med.* 40, 363–375. doi: 10.1055/a-0863-4539

Manning, W. G., and Mullahy, J. (2001). Estimating log models: to transform or not to transform? *J. Health Econ.* 20, 461–494. doi: 10.1016/s0167-6296(01)00086-8

Meyer, F., Prenleloup, A., and Schorderet, A. (2019). Development of a new embedded dynamometer for the measurement of forces and torques at the ski-binding interface. *Sensors* 19:4324. doi: 10.3390/s19194324

Minetti, A. (2016). "Concentric, isometric and eccentric contractions: which dominates alpine skiing?," in *Science and Skiing VII*, eds E. Müller, J. Kröll, S. Lindinger, J. Pfusterschmied, J. Spörri, and T. Stöggl (Maidenhead: Meyer and Meyer Sport), 23–29.

Moon, J., Koo, D., Kim, K., Shin, I., Kim, H., and Kim, J. (2015). Effect of ski simulator training on kinematic and muscle activation of the lower extremities. *J. Phys. Ther. Sci.* 27, 2629–2632. doi: 10.1589/jpts.27.2629

Morel, B., Lapole, T., Liotard, C., and Hautier, C. (2019). Critical peripheral fatigue thresholds among different force-velocity conditions: an individual-based model approach. *Front. Physiol.* 10:875. doi: 10.3389/fphys.2019.00875

Müller, E., Benko, U., Raschner, C., and Schwameder, H. (2000). Specific fitness training and testing in competitive sports. *Med. Sci. Sports Exerc.* 32, 216–220. doi: 10.1097/00005768-200001000-00032

Nemec, B., Kugovnik, O., and Supej, M. (2001). "Influence of the ski side cut on vibrations in alpine skiing," in *Science and Skiing II,* eds E. Müller, H. Schwameder, C. Raschner, S. Lindinger, and E. Kornexl (Hamburg: Verlag Dr. Kovac), 232–241.

Nilsson, J., and Haugen, P. (2004). Knee angular displacement and extensor muscle activity in telemark skiing and in ski-specific strength exercises. *J. Sports Sci.* 22, 357–364. doi: 10.1080/02640410310001641557

Noorkõiv, M., Nosaka, K., and Blazevich, A. J. (2014). Neuromuscular adaptations associated with knee joint angle-specific force change. *Med. Sci. Sports Exerc.* 46, 1525–1537. doi: 10.1249/MSS.0000000000000269

Padulo, J., Di Capua, R., and Viggiano, D. (2012). Pedaling time variability is increased in dropped riding position. *Eur. J. Appl. Physiol.* 112, 3161–3165. doi: 10.1007/s00421-011-2282-8

Panizzolo, F. A., Marcolin, G., and Petrone, N. (2013). Comparative evaluation of two skiing simulators as functional training devices for recreational skiers. *J. Sports Sci. Med.* 12, 151–158.

Pozzo, R., Canclini, A., Baroni, G., Benedetti, D., and D'Ottavio, S. (2010). "3-D kinematic and kinetics analysis of slalom in elite skiers at the Bormio World Cup ski finals in 2008," in *Science and Skiing V,* eds E. Müller, S. Lindinger, and T. Stöggl (Maidenhead: Meyer and Meyer Sport), 355–363.

Raschner, C., Schiefermüller, C., Zallinger, G., Hofer, E., and Brunner, F. (2001). "Carving turns versus traditional parallel turns–a comparative biomechanical analysis," in *Science and Skiing II,* eds E. Müller, H. Schwameder, C. Raschner, S. Lindinger, and E. Kornexl (Hamburg: Verlag Dr. Kovac), 203–217.

Rohatgi, A. (2015). *Data From: WebPlotDigitalizer: HTML5 Based Online Tool to Extract Numerical Data From Plot Images*. Available online at: https://automeris.io/WebPlotDigitizer

Stöggl, T., Kröll, J., Helmberger, R., Cudrigh, M., and Müller, E. (2018). Acute effects of an ergometer-based dryland alpine skiing specific high intensity interval training. *Front. Physiol.* 9:1485. doi: 10.3389/fphys.2018.01485

Struzik, A., Konieczny, G., Stawarz, M., Grzesik, K., Winiarski, S., and Rokita, A. (2016). Relationship between lower limb angular kinematic variables and the effectiveness of sprinting during the acceleration phase. *Appl. Bionics Biomech.* 2016:7480709. doi: 10.1155/2016/7480709

Supej, M., and Holmberg, H.-C. (2019). Recent kinematic and kinetic advances in olympic alpine skiing: pyeongchang and beyond. *Front. Physiol.* 10:111. doi: 10.3389/fphys.2019.00111

Supej, M., Kugovnik, O., and Nemec, B. (2003). Kinematic determination of the beginning of a ski turn. *Kinesiol. Slov.* 9, 5–11.

Supej, M., Saetran, L., Oggiano, L., Ettema, G., Šarabon, N., Nemec, B., et al. (2013). Aerodynamic drag is not the major determinant of performance during giant slalom skiing at the elite level. *Scand. J. Med. Sci. Sports* 23, e38–e47. doi: 10.1111/sms.12007

Turnbull, J. R., Kilding, A. E., and Keogh, J. W. L. (2009). Physiology of alpine skiing. *Scand. J. Med. Sci. Sports* 19, 146–155. doi: 10.1111/j.1600-0838.2009.00901.x

Vogt, M., and Hoppeler, H. H. (2014). Eccentric exercise: mechanisms and effects when used as training regime or training adjunct. *J. Appl. Physiol.* 1985 116, 1446–1454. doi: 10.1152/japplphysiol.00146.2013

Westfall, J., Kenny, D. A., and Judd, C. M. (2014). Statistical power and optimal design in experiments in which samples of participants respond to samples of stimuli. *J. Exp. Psychol. Gen.* 143, 2020–2045. doi: 10.1037/xge0000014

Zeglinksi, C. M., Swanson, S. C., Self, B. P., and Greenwald, R. M. (1998). Muscle activity in the slalom turn of alpine skiing and in-line skating. *Int. J. Sports Med.* 19, 447–454. doi: 10.1055/s-2007-971943

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.

frontiers in Sports and Active Living

ORIGINAL RESEARCH
published: 26 August 2020
doi: 10.3389/fspor.2020.00107

Giant Slalom: Analysis of Course Setting, Steepness and Performance of Different Age Groups — A Pilot Study

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Edited by:
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Reviewed by:
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Specialty section:
This article was submitted to Sports Science, Technology and Engineering, a section of the journal Frontiers in Sports and Active Living

Received: *19 September 2019*
Accepted: *14 July 2020*
Published: *26 August 2020*

Citation:
Bruhin B, Janssen RJF, Guillaume S, Gander M, Oberle F, Lorenzetti S and Romann M (2020) Giant Slalom: Analysis of Course Setting, Steepness and Performance of Different Age Groups — A Pilot Study. Front. Sports Act. Living 2:107. doi: 10.3389/fspor.2020.00107

Introduction: Giant slalom is the core discipline of alpine skiing, and each race has its own specific course and terrain characteristics. These variations may explain differences in the speed and time per turn profiles, which are essential for performance development and injury prevention. This study aims to address the differences in course setting and steepness of the different course sections (flat—medium—steep) and compare them to the performance parameters among young (U12, U14, U16) and older (U18, U21, elite) male athletes.

Methods: The study examined a total sample size of 57 male athletes; 7 from elite level, 11 from U21, 13 from U18, 6 from U16, 13 from U14, and 7 from U12. The athletes wore a portable global navigation satellite system (GNSS) sensor to extract performance parameters. The course profiles and gate positions of nine runs were measured with differential GNSS. The runs were divided into flat, medium and steep sections. From the performance parameters (speed, time per turn, etc.) and the course setting variables, the mean value per section was calculated and used for the further analysis.

Results: In total, 192 run sections from 88 runs were recorded and analyzed. Comparisons between course settings in young and older classes showed no significant differences. However, the turning angles and horizontal gate distances were smaller in flat sections. Average speed (49.77 vs. 65.33 km/h) and time per turn (1.74 vs. 1.41 s) differed significantly between young and U21/elite categories. In medium terrain sections U21 and elite athletes spent more time in the gliding phase compared to all other athletes.

Discussion: It seems to be a reasonable that, given similar course setting and steepness, speed increases concurrently with the technical and tactical skills of the athlete. Moreover, the finding that the elite athletes spent more time in the gliding phase could be crucial for understanding technique and performance development in young athletes.

Keywords: giant slalom, youth sports, course setting, performance, elite sports

INTRODUCTION

The four main disciplines of the World Cup of Alpine Ski Racing are slalom, giant slalom (GS), super-G and downhill. Because GS is the core discipline of alpine skiing, it was the exclusive focus of this study. Each race has its own specific course and terrain characteristics regulated by the International Ski Federation (FIS). Nevertheless, the course setting can vary greatly since the FIS only defines certain boundaries, such as the number of gates and vertical drop (VD). For example, the horizontal distance between two successive gates is not defined and appears to increase with terrain inclination (Gilgien et al., 2015). In addition, there is a slight trend toward a shorter direct gate-to-gate distance for the section of the race that increases in inclination; thus, in the flat sections, the courses are set straighter than in the steep sections for which a more sinuous course setting is usually chosen (Bruhin et al., 2018). These characteristics influence the speed of the athlete and are also associated with a decrease in speed as steepness increases as well as increased horizontal distances and shorter direct gate-to-gate distances. Spörri et al. (2012a) revealed that these characteristics can produce greater time differences among athletes than other characteristics as e.g., vertical gate distance. Moreover, course setting and terrain inclination contribute to 57% of the skier speed (Gilgien et al., 2015).

It is essential to understand course setting because it can be related to the incidence and severity of injuries in athletes. In an attempt to reduce speed, an increase in horizontal gate distance has been proposed. As Spörri et al. (2012a) revealed, this may decrease speed but it is not the best way to reduce injury incidence. Furthermore, an increased horizontal gate distance can induce fatigue as a consequence of loading forces acting for a longer duration, which tends to be the greatest upon the completion of a turn. In addition, a greater horizontal gate distance may increase the risk of off-balance situations by forcing the athlete to fatigue both the backward and inward leaning spectrum. Thus, it might be of greater benefit to an athlete's safety to locally slow down a racer for hazardous points of the course (e.g., terrain changes, key sectors). Additionally, the vertical gate distance should also be considered as this causes a decrease in skier's speed without the aforementioned drawbacks (Gilgien et al., 2020).

The FIS sets rules for course settings in GS. 11 to 15% of the VD (250 to 450 m) encompasses the number of directional changes for elite races (International Competition Rules (ICR) and Fédération Internationale de Ski (FIS), 2019). A greater number of regulations are specified for young athletes and are homogenous for the U16, U14, and U12 groups. Moreover, GS gates must be placed as follows: the distance between open gates is 22 ± 5 m with a maximum of three gates, including delayed gates, at a maximal distance of 35 m. At the delayed gates, a minimum distance of 15 m between the two consecutive gates is required. Additionally, the VD for young athletes should not exceed 300 m (National Competition Rules (NCR) and Swiss-Ski, 2019).

The National Federation of Switzerland has established specific rules regarding the course setting for young athletes. Before entering the elite competition, skiers are divided into the following age groups: U12, U14, U16, U18, and U21. It should be noted that there are no differences in course setting applied to these groups (National Competition Rules (NCR) and Swiss-Ski, 2019). The young athletes included in this study received coaching, feedback and an intense level of training and competition (Romann and Fuchslocher, 2014). Overall, while all of these factors enhance performance, it is known that intensive ski training is physically demanding, and there is a high risk of injury independent of age and gender (Spörri et al., 2017). To prevent this, a specific training regimen should be incorporated (Müller et al., 2017), and knowledge of performance and course setting becomes more valuable.

In addition to injury prevention, a progressive transition for young athletes to the elite level is important; therefore, specific data on each age category are necessary for coaches and race organizers. Since course setting has a major influence on the athlete's speed, it is essential to thoroughly examine these characteristics (Spörri et al., 2012a; Gilgien et al., 2020). The FIS sets regulations on the slope and course settings for elite, U21 and U18 athletes, and the National Federation specifies young race conditions.

To our knowledge there is no study which compares the course conditions (course setting, steepness) according to the aforementioned rules in young vs older athletes. Neither a study which focuses on the differences on the performance (e.g., turn phases, speed, time per turn) of young vs. older athletes. Therefore, the aim of the present study was to identify differences in sections of the runs (course setting, steepness) and performance parameters (e.g., speed, time per turn, turn phases etc.) among young and older athletes. The application of these procedures is predicted to improve knowledge about performance development and injury prevention in the context of GS.

MATERIALS AND METHODS

Participant Characteristics

Measurements were taken for six age levels, which included a total sample size of 57 male athletes; seven were from the elite level (all of the elite athletes were older than 21 y), 11 were from the U21 level, 13 were from U18, 6 were from U16, 13 were from U14, and 7 were from U12. The elite skiers were born in 1992 ± 2.18 y and had a mean world ranking of 49 ± 69.02 (min: 5; max: 152). In accordance with the rules of the international federation (International Competition Rules (ICR) and Fédération Internationale de Ski (FIS), 2019), the groups elite, U21 and U18 are combined in some evaluations to "older group" and the groups U16, U14, and U12 as JO (Abbreviation from Swiss Ski Federation: Jugend Organization = youth organization) group. Especially for the race analysis this makes sense, because the boys participated together in the JO races and the older group in the FIS races.

Race Description

The measurements were taken at three different locations during the 2018–2019 and 2019–2020 winter seasons. In Hoch-Ybrig (Schwyz, Switzerland) at the Swiss National Championships on

March 23–24, 2019 and a FIS race on January 14, 2020. The VD for this hill is officially recorded as 295 m. In Les Diablerets (Vaude, Switzerland) at a FIS race on February 8, 2020 with a VD of 340 m. In Meiringen (Bern, Switzerland) at regional races from January 19, 2019 and January 26, 2020 and the VD for this hill is 264 m. With the exception of the race in Meiringen on January 26, 2020, all races consisted of two runs. **Table 1** shows the included athletes per age group and per race.

Course Setting Parameters

Each gate was measured with a global navigation satellite system (GNSS) device in differential mode (Gilgien et al., 2015). The geodetic coordinates of the gates were determined in post-processing with L1 carrier-phase data, carried out with two u-blox M8 GNSS receivers. One receiver was used as static reference. The second was used as rover (baseline < 2 km). The differential fixed ambiguities carrier-phase post-processing was carried out with the Free and Open-Source Software (FOSS) RTKLIB v.2.4.2 in order to achieve an accuracy of 5 cm.

All course setting parameters were calculated based on the coordinates of each gate (Gilgien et al., 2015). The gate distance is the linear distance between two gates. The horizontal gate distance is defined as a perpendicular line from one gate to the lines between the previous and subsequent gates. The vertical gate distance describes the distance from one gate to the beginning of the perpendicular line. The turning angle is calculated as the angle between the extended lines from two consecutive gates to the line of the gate to the next gate, according Gilgien et al. (2015). The steepness is defined as the difference between two consecutive turns and the section steepness is the average value per section.

Performance Parameters

All athletes had a portable GNSS sensor on their back protectors. The sensor is shown in **Figure 1** and was attached to the back protector with double-sided adhesive tape at the height of the third thoracic vertebrae. For safety reasons, it was placed next to the spine. To address to the performance parameters, the speed (km/h) information and trajectory of the entire run were analyzed.

Calculated Variables

In collaboration with expert coaches, a turn was defined as the start of a turn to the start of the next turn. The start of a new turn was set when the fitted radius first dropped below 80 m. The minimal turn radius was set as the apex of the turn, and the end of the turn was determined as the point at which the turn radius exceeded 80 m again for the first time (**Figure 2**). The start of the turn to the minimal turn radius was identified as the initiation, the minimal turn radius to the end of the turn was identified as the completion and the end of the turn to the start of the next turn was identified as the gliding phase. The relative amounts of time spent in the respective turn phases from each athlete during the entire turn were calculated. These ratios were averaged along the entire run.

Based on the fitted trajectory of the athlete, several parameters of one turn [time of the start of the turn (s), minimal turn radius (m) and time of the end of the turn (s)] were calculated. Based on these defined points, the per-turn calculations could be conducted for the following variables: (a) the decrease in speed during the initiation phase and (b) the speed increase from the minimal turn radius to the beginning of the next turn. Both were expressed as a percentage of the start speed in the specific turn.

Parameter Computation

In total, 88 runs were measured, and each run was analyzed as an individual measurement. Twenty-six athletes performed one run, 31 athletes performed two runs. At each of the nine races, the track profile was analyzed. According to conspicuous terrain transitions the sections of the run were divided into three different categories (flat, medium, steep) (Bruhin et al., 2018). The section was assigned to "flat" if the average steepness of

TABLE 1 | Athletes and sections of all competitions.

		2019_HY_ run1	2019_HY_ run2	2020_HY_ run1	2020_HY_ run2	2020_LesD_ run1	2020_LesD_ run2	2019_M_ run1	2020_M_ run1	2020_M_ run2	Total
Number of athletes per run	Elite	4	4	2	1	1					12
	U21			5	5	6	4				20
	U18			5	7	5	3				20
	U16							3	1	3	7
	U14							8	4	5	17
	U12							2	5	5	12
	Total	4	4	12	13	12	7	13	10	13	88
Number of sections per run		3	3	3	3	3	3	1	1	1	21
Turns per section	Flat	17	17	21	21	10	10				96
	medium	19	19	17	17	16	16	42	37	36	219
	steep	6	6	4	4	19	19				58
Total number of mean values per race		12	12	36	39	36	21	13	10	13	192

HY, Hoch-Ybrig; LesD, Les Diablerets; M, Meiringen.

FIGURE 1 | Details of the GNSS Sensor; dimensions: 65 × 35 × 15 mm; weight: 35 g.

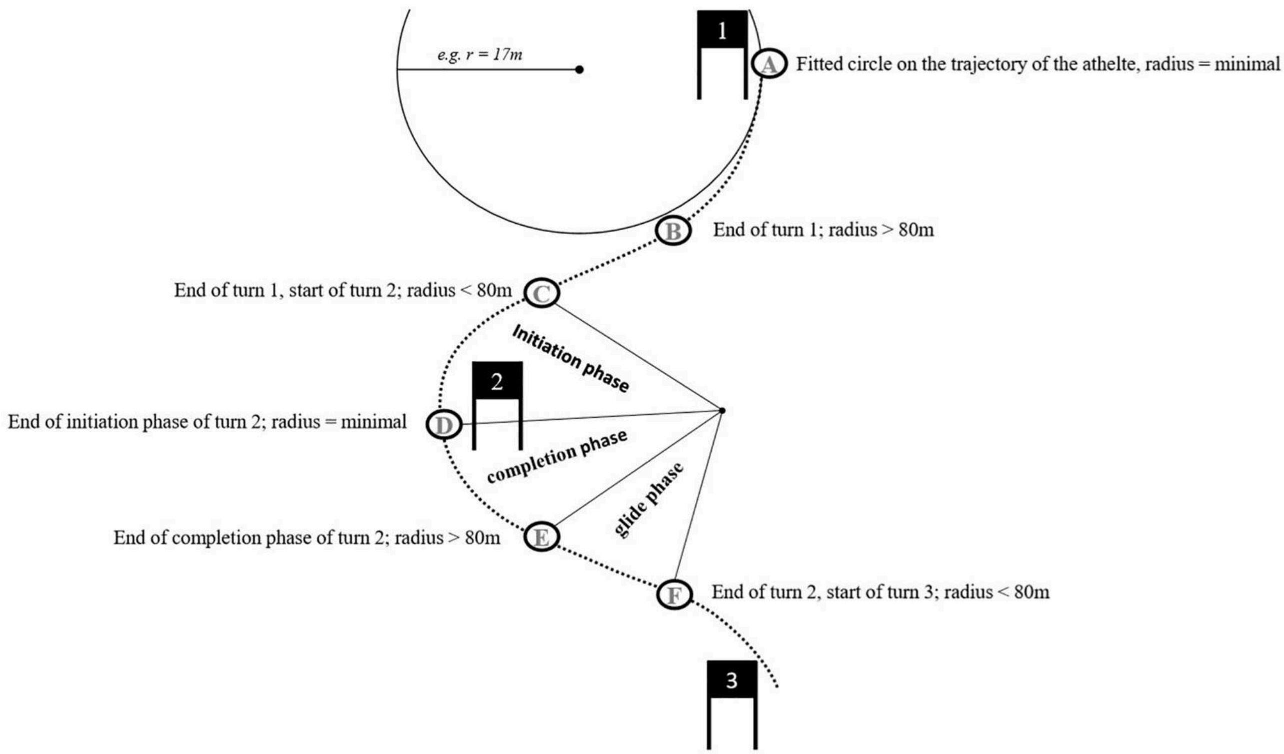

FIGURE 2 | Definition of characteristic points in a skier's trajectory and turn phases.

the section was lower than 13.5°, to "medium" if the average steepness of the section was between 13.5° and 18.9° and to "steep" if the average steepness of the section was above 18.9°. The results of this division can be seen in **Table 2**. A total of 21 sections were analyzed. All the athletes' turns within one section of a course were averaged. These average values per section and per athlete were treated as measured values in the subsequent analysis.

Statistics

The Levene's test assessed the equality of variances. Afterwards, for all results, a one-way analysis of variance (ANOVA) was performed to identify any significant differences. Finally, as *post-hoc* tests, the Student's t-test with Bonferroni correction was used for equal and unequal variances while for unequal variances, the Welch's t-test was selected. All tests were conducted in SPSS (IBM SPSS Statistics for Windows, Version 25.0, Armonk, NY, 2017).

TABLE 2 | Course setting parameters (average and standard deviation) per run and terrain section.

	Flat	Medium	Steep	Older group_ medium	JO_ medium	2019_M_ JO_ boys	2020_M_ JO_run1	2020_M_ JO_run2	2020_LesD_ FIS_run1	Flat	Medium	Steep	2020_LesD_ FIS_run2	Flat	Medium	Steep
Gate distance (m)	27.08	25.34	26.08	26.32	25.07	26.87	23.67	24.29	26.35	25.01	25.49	27.57	25.40	25.75	24.98	25.56
Std	1.45	1.78	2.37	3.68	3.67	2.34	3.01	4.61	3.14	2.76	4.14	1.46	4.54	5.84	4.00	4.17
Steepness (°)	−11.96	−16.24	−20.62	−15.29	−16.60	−14.66	−17.84	−17.72	−16.91	−12.95	−14.60	−20.53	−16.85	−12.95	−14.66	−20.55
Std	1.40	1.09	1.04	6.45	5.19	4.97	5.10	4.81	5.81	7.25	5.30	2.31	5.51	6.10	4.86	2.68
Turning angle (θ)	25.58*/**	31.51*	33.48**	31.87	32.23	31.70	32.42	32.69	29.67	26.51	28.43	32.03	29.50	25.26	27.97	32.54
Std	1.93	1.74	1.19	10.87	9.35	8.36	9.41	10.36	8.21	11.55	7.39	6.01	8.24	10.45	7.22	6.49
Vertical gate distance (m)	25.88	23.96	24.94	25.05	23.98	25.78	22.61	23.15	25.30	23.06	25.07	26.47	24.65	25.09	24.56	24.49
Std	1.47	1.11	2.30	3.86	3.66	2.43	3.02	4.54	3.37	3.98	3.97	1.56	4.50	5.80	3.93	4.14
Horizontal gate distance (m)	5.81*/**	6.89*	7.36**	7.18	6.92	7.28	6.61	6.80	6.70	5.62	6.20	7.55	6.26	5.08	5.96	7.08
Std	0.51	0.35	0.55	2.67	2.21	1.89	2.05	2.64	2.11	2.77	1.98	1.40	2.25	2.86	1.79	1.86
	2019_HY_ FIS_run1	**flat**	**medium**	**steep**	**2019_HY_ FIS_run2**	**flat**	**medium**	**steep**	**2020_HY_ FIS_run1**	**flat**	**medium**	**steep**	**2020_HY_ FIS_run2**	**Flat**	**Medium**	**Steep**
Gate distance (m)	26.15	27.27	25.08	25.83	26.55	27.19	26.97	25.55	27.58	28.30	26.60	28.32	27.85	28.99	27.50	23.64
Std	1.02	1.35	0.98	0.72	1.18	3.35	0.98	0.75	2.98	1.80	3.87	1.63	3.54	2.58	2.01	7.31
Steepness (°)	−13.81	−11.39	−14.29	−19.07	−14.66	−11.50	−15.67	−20.41	−14.83	−11.31	−17.35	−21.72	−14.73	−11.66	−16.58	−21.45
Std	6.39	3.89	7.43	4.61	4.97	3.80	3.91	4.32	7.13	7.02	5.20	4.82	6.80	4.82	7.27	4.85
Turning angle (θ)	26.66	22.27	28.81	33.76	31.70	28.55	33.47	35.85	30.06	24.70	36.46	32.59	30.71	26.21	35.48	34.09
Std	11.07	7.68	13.01	7.66	8.36	6.87	9.07	6.72	10.19	8.95	8.62	4.98	11.14	12.12	7.52	8.73
Vertical gate distance (m)	25.29	26.69	24.01	24.72	25.78	26.33	25.73	24.27	25.80	26.06	25.12	27.17	26.85	28.06	26.42	22.52
Std	3.38	1.37	4.59	1.24	2.43	3.25	1.37	0.78	4.50	5.03	4.15	1.34	3.55	2.67	1.65	7.25
Horizontal gate distance (m)	6.08	5.25	6.55	7.17	7.28	6.64	7.75	7.84	6.90	5.68	8.24	7.91	7.31	6.58	8.39	6.59
Std	2.49	1.86	2.90	2.04	1.89	1.65	2.04	1.47	2.49	2.32	2.06	1.50	2.76	3.01	1.86	3.00

*In the first three columns the average and standard deviation per category (flat, medium, steep) for all races are shown. Significant ($p < 0.05$) differences between groups are marked with an asterisk (*flat vs medium, **flat vs steep). HY, Hoch-Ybrig; LesD, Les Diablerets; M, Meiringen.*

RESULTS

Course Setting Parameters

In total, 192 run sections from 88 runs were recorded and analyzed. Comparisons in course setting between JO and the older classes were only made in the medium sections, due to the different number of observations. No significant difference was found between the JO and the older group.

The average values of the different section categories for all competitions are shown in **Table 2**. The sections differed in steepness, and the turning angle was smaller in the flat condition compared to the medium and steep condition. In addition, the horizontal gate distance in flat conditions was smaller than in medium and steep conditions where gates are set with a larger horizontal offset. No significant difference in the course setting parameters could be detected between the steep and medium conditions.

Regarding U18, U21 and elite competitions in steep terrain (**Table 3**); the gate-gate distance as well as the vertical gate distance were significantly shorter in the elite races (gate-gate distance = 25.7 m; vertical gate distance = 24.9 m) than in the races of the U21 and U18 group (gate-gate distance = 27.3 m; vertical gate distance = 26.2 m). Therefore, the turning angle did not differ significantly.

Performance Parameters

The JO group only had medium terrain sections and in order to obtain comparability among the younger and older athletes, they are compared in the medium terrain section. The older athletes are compared in all three sections.

All Athletes in Medium Terrain Section

The time needed per turn (**Table 4**) differed between the defined age groups in a range of 1.74 s (U12) and 1.41 s (elite). The elite group had the lowest time per turn and differed significantly from the three young groups (U12, U14, and U18). The youngest group (U12) needed significantly the most time per turn, compared to all groups. Furthermore, the U14 group had a significantly higher time per turn than the U21 group.

The average speed range (**Table 4**) was between 49.77 km/h (U12) and 65.33 km/h (U21). The older group showed a significantly higher average speed than the JO group. In addition, the U21 group had a significantly higher speed than the U18 group. Also, the U16 exhibited a significantly higher average speed than the U14 and the U12 age groups and the U14 reached a higher speed than the U12 group.

Speed gain and speed decrease between two turn phases are displayed in **Figure 3**. No significant differences were found in the acceleration and deceleration phase, respectively.

Relative time spent in the different turn phases of all groups are shown in **Table 5**, **Figure 4**. The youngest group (U12) spent significantly more relative time in the initiation phase than the U14 and the elite group. Older athletes spend less time in the completion phase and more in the gliding phase compared to the JO group in the medium terrain section. With the exception between U18 and U16, all results were significant

TABLE 3 | Course setting parameters (average and standard deviation) per age group and terrain section.

	Elite	FIS	JO	Elite (flat)	Elite (medium)	Elite (steep)	FIS (flat)	FIS (medium)	FIS (steep)	JO (medium)
Gate distance (m)	26.35	27.02	25.07	26.87	26.08	**25.69**	27.23	26.49	**27.31**	25.07
Std	2.48	3.49	3.67	1.37	3.42	0.75	3.60	3.84	2.78	3.67
Steepness (°)	−14.23	−15.88	−16.60	−11.45	−14.96	−19.74	−12.89	−15.53	−20.70	−16.60
Std	5.75	6.41	5.19	3.84	6.02	4.52	5.93	6.74	2.91	5.19
Turning angle (θ)	29.21	29.94	32.23	25.41	31.21	34.81	26.70	32.34	32.25	32.23
Std	10.11	9.44	9.35	7.93	11.40	7.28	9.52	10.45	6.23	9.35
Vertical gate distance (m)	25.54	25.89	23.98	26.51	24.89	**24.49**	26.20	25.16	**26.20**	23.98
Std	2.94	3.86	3.66	2.50	3.46	1.06	4.20	4.11	2.80	3.66
Horizontal gate distance (m)	6.68	6.85	6.92	5.95	7.15	7.50	6.15	7.20	7.50	6.92
Std	2.29	2.41	2.21	1.89	2.58	1.81	2.43	2.73	1.63	2.21

Significant ($p < 0.05$) differences between groups are marked in bold (= elite vs. FIS, JO).

TABLE 4 | Performance parameters (average and standard deviation); time per turn (s) and speed (km/h) for all groups in the medium terrain sections.

		U12	U14	U16	U18	U21	Elite
Time per turn (s)	Mean	1.74^#+!!″‡	1.58^*″‡	1.56*	1.55^*‡	1.49^*#	1.41^*#!!
	Std	0.10	0.11	0.08	0.09	0.07	0.13
Speed (km/h)	Mean	49.77^#+!!″‡	54.00^*+!!″‡	55.60^*#!!″‡	62.13^*#+″	65.33^*#+!!	61.30^*#+
	Std	1.91	1.23	1.13	2.71	3.02	4.77

Significant ($p < 0.05$) differences between groups are marked by group-specific markers (U12^*; U14^#; U16^+; U18^!!; U21^″; Elite^‡).

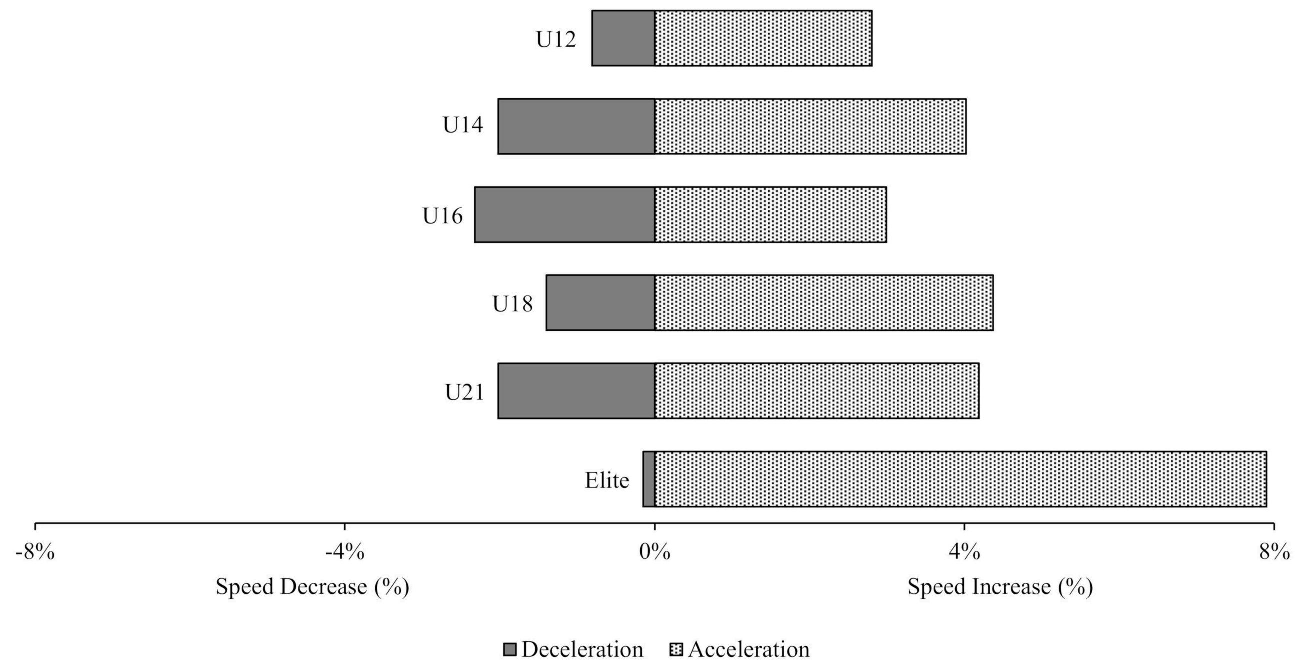

FIGURE 3 | Mean percentage of the difference in speed between two turn phases in the medium terrain section; the acceleration phase refers to the section from the minimal radius to the start of the next turn; the deceleration phase is from the start of the turn to the minimal radius.

TABLE 5 | Mean percentage for all groups in medium terrain for the initiation, completion and gliding phases, expressed as a percentage of the total turn cycle.

		U12	U14	U16	U18	U21	Elite
Initiation phase (%)	Mean	44.02$^{\#''}$	41.22*	43.70	42.67	40.93*	41.85
	Std	2.27	2.61	4.05	3.02	3.18	3.21
Completion phase (%)	Mean	43.10$^{!!''\ddagger}$	43.58$^{!!''\ddagger}$	42.02$^{''\ddagger}$	39.20$^{*\#}$	38.44$^{*\#+}$	37.83$^{*\#+}$
	Std	1.54	2.10	3.05	2.10	2.74	2.16
Gliding phase (%)	Mean	12.88$^{\#!!''\ddagger}$	15.19$^{*!!''\ddagger}$	14.28$^{!!''\ddagger}$	18.12$^{*\#+}$	20.62$^{*\#+}$	20.32$^{*\#+}$
	Std	1.84	1.36	1.60	3.76	4.90	4.22

Significant ($p < 0.05$) differences between groups are marked by group-specific markers (U12*; U14$^{\#}$; U16^{+}; U18$^{!!}$; U21$^{''}$; Elite‡).

in the completion phase. Furthermore, the gliding phase differed significantly between the JO and the U18, U21, elite groups.

Older Athletes in Three Terrain Sections

Zoomed in on the older group, no significant differences were found in the initiation phase in the three terrain sections (**Figure 5**). In the completion and gliding phase, significant differences were found in the flat terrain section. Elite athletes spent less relative time in the completion phase than the U21 group (**Figure 6**) and more time in the gliding phase compared to the athletes from the U18 group (**Figure 7**).

DISCUSSION

The main finding of the study was that average course settings in young classes (U12, U14, U16) did not differ in comparison with the older classes (U18, U21, elite). However, compared to the medium and steep sections, the turning angles and horizontal gate distances were shorter in the flat sections. Average speed for the medium terrain section was between 49.77 km/h (U12) and 65.33 km/h (U21) and time per turn differed significantly between 1.74 s (U12) and 1.41 s (elite). Additionally, differences were found in the mean speed and turn phase parameters, more precisely in the gliding and completion phases. In medium terrain sections U21 and elite athletes spent more time in the gliding phase compared to all other athletes.

A "high skiing speed" is commonly called a major course-related injury factor (Spörri et al., 2017). As stated in the literature (Spörri et al., 2012a), shorter linear gate distances and higher steepness correlate with decreased speed. Furthermore, it is supported by previous research that an increased horizontal distance is associated with decreased speed (Spörri et al., 2012a). Spörri et al. (2017) have also postulated that an increased horizontal gate distance is associated with a potentially increased risk of injury. This is provoked by increased fatigue and greater risk of "out-of-balance" situations.

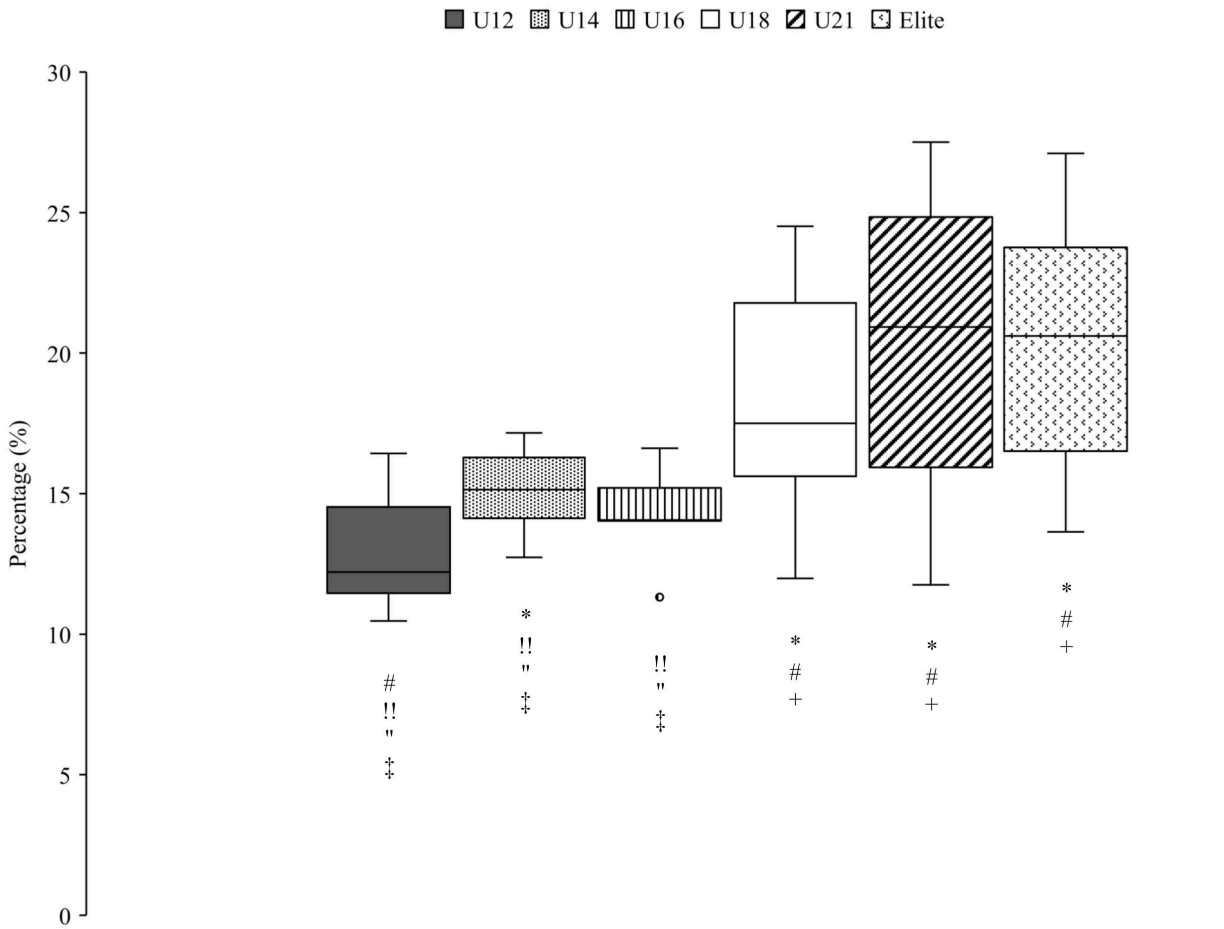

FIGURE 4 | Percentage of all groups in the gliding phase of the medium terrain section, expressed as a percentage of the total run time. Significant ($p < 0.05$) differences between groups are marked by group-specific markers (U12*; U14#; U16+; U18!!; U21″; Elite). Outliers are shown with a circle, filled with the color of the corresponding group.

When compared to the older athletes, the JO group exhibited significantly lower velocities and longer time per turn, but the horizontal gate distance was not significantly larger. Gilgien et al. (2015) stated that 57% of a skiers speed can be explained by course setting and terrain inclination. The technical skills of the older athletes were significantly better compared to the JO group. In addition, the older group was longer in the gliding phase. It seems to be a reasonable relation that with similar course setting and steepness, the speed increases with the technical and tactical skills of the athletes.

In this context the course setting in the measured races can be critically undermined. It seems that the extremes of development (U12 and elite) should be more clearly differentiated in order to achieve a skill transfer and to reduce injury risk. Furthermore, it can be discussed whether interventions should be taken to adjust the course setting in both levels. In the elite's course setting our results support Spörri et al. (2012a), that a larger horizontal distance is proposed to reduce the speed. In the JO's course a shorter gate distance is proposed to reduce the time per turn.

Course Setting Parameters

Gilgien et al. (2015) measured the course setting and terrain characteristics during seven male World Cup races in the winter seasons of 2010–2011 and 2011–2012, with a total of 14 runs. Gate-gate distance was recorded as 26.24 ± 2.25 m, horizontal gate distance was 7.47 ± 2.93 m and steepness was 17.80° ± 7.0° (Gilgien et al., 2015). Compared to the present findings of the older groups, it can be concluded that the horizontal distance of 6.79 ± 2.38 m, steepness of −15.34° ± 6.25° and gate-gate distance of 26.80 ± 3.21 m were comparable to the values in the literature. However, the course setting values for the JO athletes were slightly different (gate-gate distance 25.07 ± 3.67 m; horizontal gate distance 6.92 ± 2.21 m) than the values of the older group (gate-gate distance 26.32 ± 3.68 m; horizontal gate distance 7.18 ± 2.67 m) in the medium terrain section. This follows the literature since stricter regulations are applied for these age groups (National Competition Rules (NCR) and Swiss-Ski, 2019).

The horizontal gate distance for the older groups in flat conditions (5.81 ± 0.51 m) was smaller than in medium (6.89

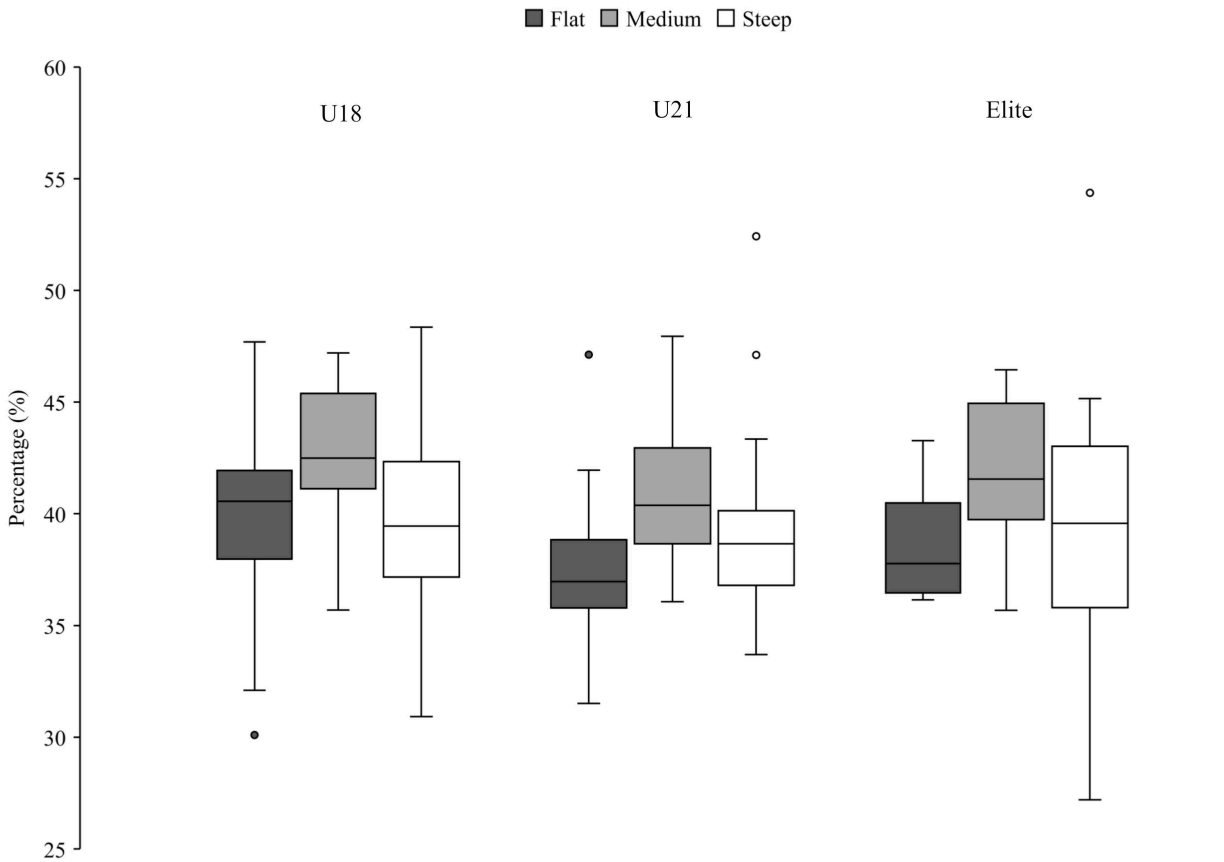

FIGURE 5 | Percentage of the U18, U21 and elite group in initiation phase, expressed as a percentage of the total run time. No ($p < 0.05$) significant differences were found among these three groups. Outliers are shown with a circle, filled with the color of the corresponding group.

± 0.35 m) and steep conditions (7.36 ± 0.55 m), where gates were set with a larger horizontal distance. The turning angle is described as the gate-gate distance, the vertical gate distance and the horizontal gate distance. Since there were neither significant differences in the gate distance, nor in the vertical gate distance, it can be stated that the turning angle is mainly influenced by the horizontal distance.

Performance Parameters

Besides differences in the course profile, the time the athletes needed per turn in the medium terrain section decreased with higher age groups (**Table 4**). The U12 group needed 1.74 ± 0.1 s and the elite athletes 1.41 ± 0.13 s. When comparing the results of the elite group to an earlier work of Spörri et al. (2012b); an average of 1.41 s/turn in the present study for the elite athletes compared to 1.68 s/turn (Spörri et al., 2012b), a trend to a smaller time per turn can be observed. The decrease in time per turn can be explained by the constant course setting. Although the turning angles and the horizontal gate distance were larger, these parameters did not differ significantly between the JO and older group. However, speed differed significantly in the medium terrain section and therefore it can be assumed that a similar distance is traveled at a higher speed and therefore the time per turn must be smaller. The decreasing trend in time per turn and increasing trend of higher speed indicate evidence of smooth skill transfers from the young athlete level to the elite level.

The difference in speed gain and speed decrease in the medium terrain section was not significant between any group but there seemed to be a tendency in elite athletes to brake less hard to the center of the turn and then take more speed out of the turn than all younger athletes (**Figure 3**). However, as mentioned, these differences are not significant and needs to be tested with a larger sample.

It is notable that the elite athletes did not have the highest speed of all groups in the medium terrain section. The lowest average speed was reached by the U12 athletes, the highest speed by the U21 athletes and in between there was an increasing trend (**Table 4**). Importantly, it should be mentioned that the sections were in the same category (medium) but did not have the same inclination. The sections of the competitions (**Table 3**) in which the elite athletes participated (−14.29°; −15.67°) were below the average value of all races (−16.24° ± 1.09°).

The changes in speed during turns in the medium terrain section was not significant between the groups (**Figure 3**). Nevertheless, a slight trend could be observed, the elite group had a small speed decrease to the minimal radius and a high increase

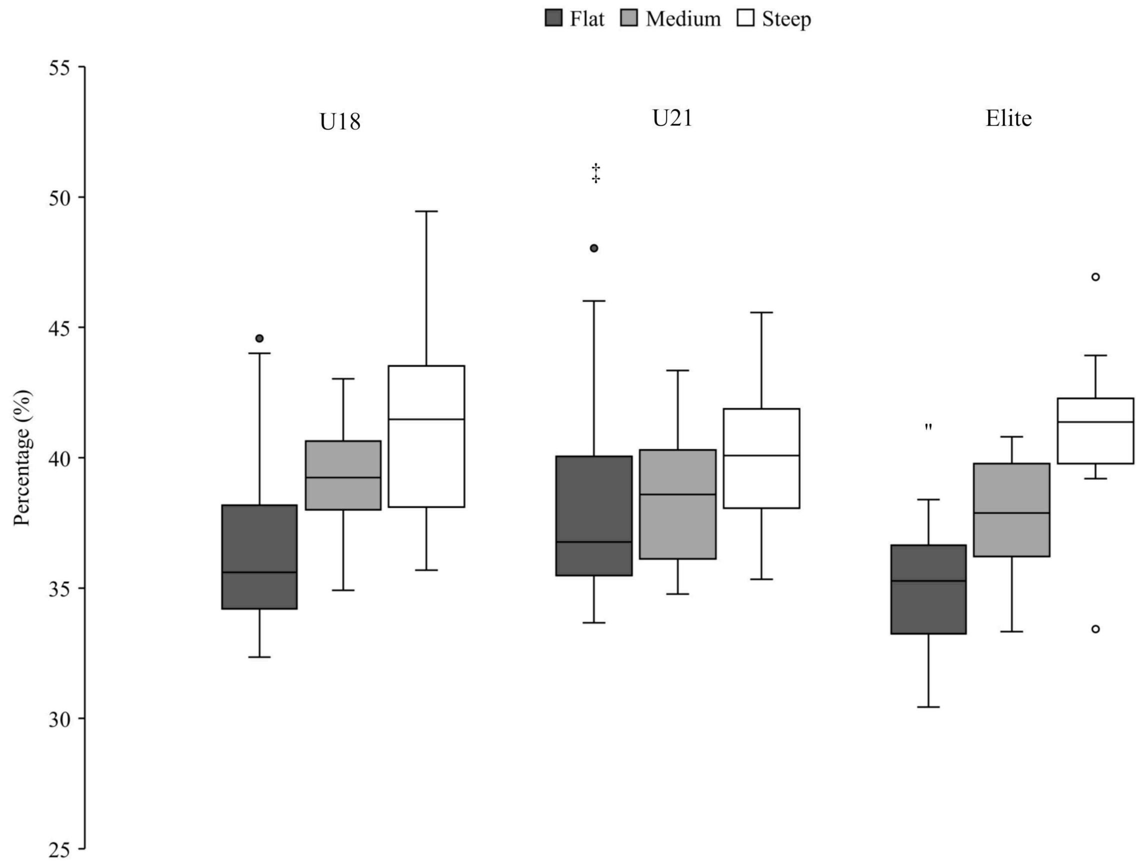

FIGURE 6 | Percentage of the U18, U21 and elite group in the completion phase, expressed as a percentage of the total run time. Significant ($p < 0.05$) differences between groups are marked by group-specific markers (U18‼; U21″; Elite). Outliers are shown with a circle, filled with the color of the corresponding group.

of speed to the next turn. Supej et al. (2011) suggested a "speed barrier" as a possible explanation for this. Elite athletes try to increase their speed after the apex of the turn and braked less before the apex of the turn to reach the goal of maintaining the highest speed possible. With a larger horizontal offset, the speed decreases prior to the apex of the turn should be larger (Spörri et al., 2012a). In one study (Spörri et al., 2012a), this larger offset was seen to potentially increase fatigue in the athlete. In terms of the present study's results, it can be assumed that higher speed variations are more demanding for the athletes and will increase their fatigue.

The gliding phase (**Table 5**) was longest in the older groups than in the JO group. Thus, a closer look was taken at the two turn phases initiation and completion. It was shown that the older athletes compensated the longer gliding phase with a shorter completion phase. Few differences were found in the initiation phase.

This study is the first to calculate tactical parameters, such as relative time in each turn phase, in this way. Spörri et al. defined the segments of the turn differently (Spörri et al., 2012a); due to a lack of information about the skier's trajectory, the turn segments could not be defined in the same way and required a new definition. It should be noted that in an earlier study (Spörri et al., 2012b) a similar initial phase (and then a shorter final phase) led to better performance as well. Moreover, in the present study there was a difference between the older group and the JO athletes in terms of gliding time. Compared to the JO group, the older groups, spent less time in the completion and more time in the gliding phase. In **Figures 6**, **7** the older groups are shown in the different terrain sections. It is notable that the same pattern appeared in flat, medium and steep sections. The gliding phase was longest in the flat terrain, shortest in the steep terrain and in between in medium terrain (**Figure 7**). The reverse pattern could be seen in the completion phase (**Figure 6**). The longest completion phase was in steep terrain, the shortest completion phase was in flat terrain and in between values for completion phase in the medium terrain sections.

Limitations

All terrain sections in the course of the JO group were labeled as medium which restricted us to make comparisons between JO and the older groups in the flat and steep terrain sections. Overall, the findings of this pilot study should be confirmed by observing identical athletes in a repeated measurement design. This would lead to a greater number of measurements and allow a turn by turn analysis to confirm these outcomes.

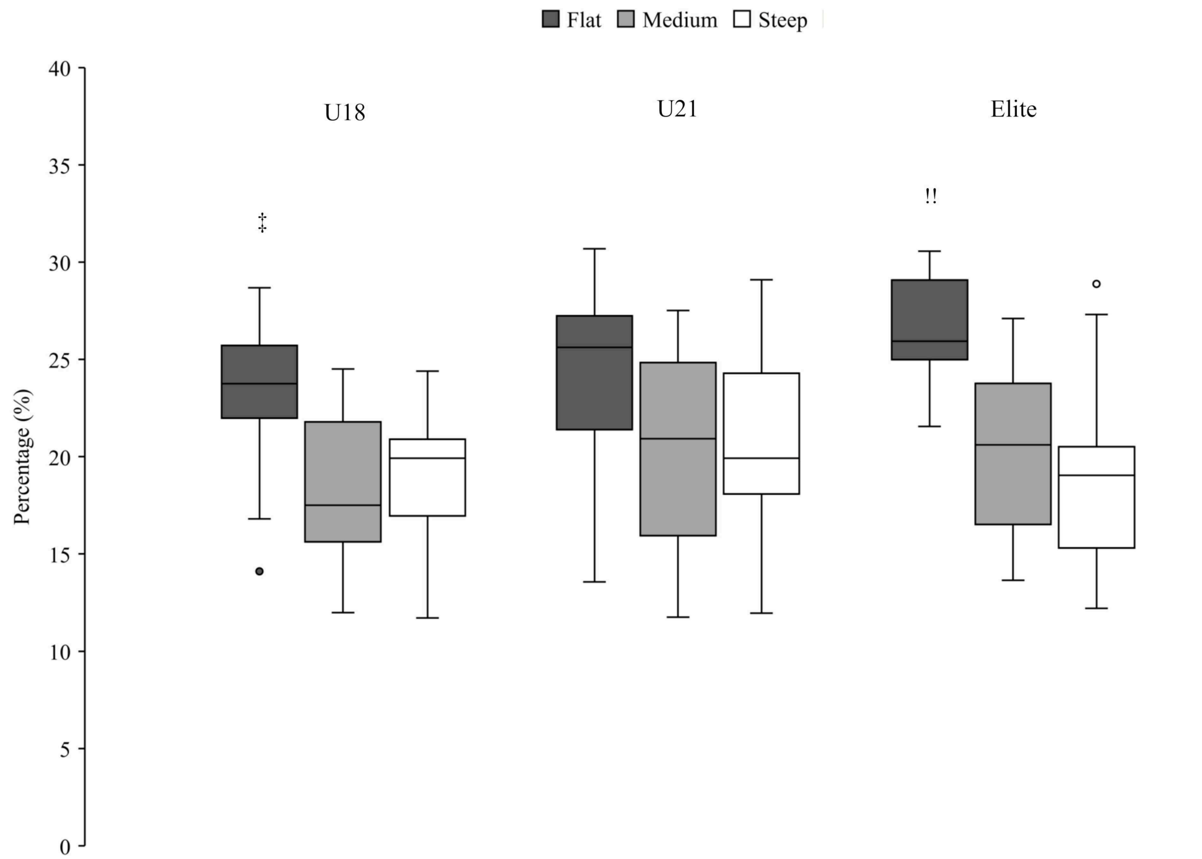

FIGURE 7 | Percentage of the U18, U21 and elite group in the gliding phase, expressed as a percentage of the total run time. Significant ($p < 0.05$) differences between groups are marked by group-specific markers (U18!!; U21″; Elite). Outliers are shown with a circle, filled with the color of the corresponding group.

Course setting and performance parameters were measured with a GNSS device. The use of a geodetic, multi-frequency receiver providing differential position solutions could result in greater accuracy. Due to the limited amount of time between the runs and the time-consuming aspect of acquiring data for the course setting parameters, this was not applicable in the present study. Gløersen et al. (2018) compared these systems and concluded that the present methods were inferior, but typical, instantaneous speed differences could be obtained with a maximal horizontal error of 2.09 m, a maximal vertical error of 2.71 m and a time precision of 0.30 s. However, an inverse relationship was found between measurement error and skiing speed which indicates larger errors at lower speeds. No low speeds were observed during the runs and the given error was overestimated in the present study.

CONCLUSION

The current study showed no differences in course setting between young and older groups. However, differences were found in the mean speed and turn phase parameters, more precisely in the completion and gliding phases. Results of this analysis form a basis to critically discuss the course setting, because they directly influence relevant performance parameters like speed and turning angles in the different age categories. Additionally, steepness influences the tactical strategy of young and older athletes in GS, which is important within the context of skills development. The tactics used within a turn were different between young and older athletes which gives coaches new areas to work on with their athletes. Moreover, the finding that the older athletes spent more time in the gliding phase could be crucial for understanding technique and performance development in young athletes.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by swissethics. Written informed consent from the participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

SL and SG advised in planning the experimental setup and selection of the methods and materials. BB and MG did the YOUNG experiment. BB and RJ carried out the ELITE experiment. BB and RJ wrote the manuscript with the help of MR. FO did the main part of the data analysis. MR and SL supervised the project. BB and RJ contributed equally to this manuscript. All authors contributed to the article and approved the submitted version.

ACKNOWLEDGMENTS

We would like to thank Christian Locher, Edouard Koehn, Gustav Bruhin, as well as the coaches and race organizers for their support.

REFERENCES

Bruhin, B., Senn, I., Flury, S., Boffi, G., Wolfsperger, F., and Lorenzetti, S. (2018). "A systematic race course analysis and a description of Men's race performance in the Paralympic alpine skiing world cup slalom and giant slalom races of the 2014/15 and 2015/16 seasons," in *Science and Skiing VII* (Meyer & Meyer Sport) 52–60.

Gilgien, M., Crivelli, P., Kröll, J., Luteberget, L. S., Müller, E., and Spörri, J. (2020). Preventing injuries in alpine skiing giant slalom by shortening the vertical distance between the gates rather than increasing the horizontal gate offset to control speed. *Br. J. Sports Med.* 54, 1042–1046. doi: 10.1136/bjsports-2019-101692

Gilgien, M., Crivelli, P., Spörri, J., Kröll, J., and Müller, E. (2015). Characterization of course and terrain and their effect on skier speed in World Cup alpine ski racing. *PLoS ONE.* 10:e0118119. doi: 10.1371/journal.pone.0118119

Gløersen, Ø., Kocbach, J., and Gilgien, M. (2018). Tracking performance in endurance racing sports: evaluation of the accuracy offered by three commercial GNSS receivers aimed at the sports market. *Front. Physiol.* 9:1425. doi: 10.3389/fphys.2018.01425

International Competition Rules (ICR), and Fédération Internationale de Ski (FIS). (2019). Available online at: https://assets.fis-ski.com/image/upload/v1542267129/fis-prod/IWO_Juli_2018_15112018.pdf (accessed Apr 28, 2019).

Müller, L., Hildebrandt, C., Müller, E., Fink, C., and Raschner, C. (2017). Long-term athletic development in youth alpine ski racing: the effect of physical fitness, ski racing technique, anthropometrics and biological maturity status on injuries. *Front. Physiol.* 8:656. doi: 10.3389/fphys.2017.00656

National Competition Rules (NCR), and Swiss-Ski (Swiss Ski Federation). (2019). Available online at: https://www.swiss-ski-kwo.ch/docs/WR2019_Alpin.pdf (accessed Apr 28, 2019).

Romann, M., and Fuchslocher, J. (2014). The need to consider relative age effects in women's talent development process. *Percept. Mot. Skills.* 118, 651–662. doi: 10.2466/30.10.PMS.118k24w8

Spörri, J., Kröll, J., Gilgien, M., and Müller, E. (2017). How to prevent injuries in alpine ski racing: what do we know and where do we go from here? *Sports Med. Auckl NZ.* 47, 599–614. doi: 10.1007/s40279-016-0601-2

Spörri, J., Kröll, J., Schwameder, H., and Müller, E. (2012b). Turn characteristics of a top world class athlete in giant slalom: a case study assessing current performance prediction concepts. *Int. J. Sports Sci. Coach.* 7:647–659. doi: 10.1260/1747-9541.7.4.647

Spörri, J., Kröll, J., Schwameder, H., Schiefermüller, C., and Müller E. (2012a). Course setting and selected biomechanical variables related to injury risk in alpine ski racing: an explorative case study. *Br. J. Sports Med.* 46, 1072–1077. doi: 10.1136/bjsports-2012-091425

Supej, M., Kipp, R., and Holmberg, H.-C. (2011). Mechanical parameters as predictors of performance in alpine World Cup slalom racing. *Scand. J. Med. Sci. Sports.* 21:e72–e81. doi: 10.1111/j.1600-0838.2010.01159.x

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