YOUTH AND WINTER SPORTS

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YOUTH AND WINTER SPORTS

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EDITORIAL
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Editorial: Youth and Winter Sports

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Keywords: winter sports, physiology, biomechanics, congress, Olympic, youth

Editorial on the Research Topic

Youth and Winter Sports

CONGRESS "YOUTH AND WINTER SPORTS"

Just before the beginning of the COVID-19 pandemic, Lausanne—known as the "Olympic capital" since it is the home of the International Olympic Committee—had the privilege and opportunity to organise the last international sporting event not affected by the virus. The 2020 Winter Youth Olympic Games was the third edition of the Winter Youth Olympic Games (YOG) and was held in Lausanne between January 9 and 22, 2020. The event featured 8 sports and 16 disciplines, including ski mountaineering and women's Nordic combined for the first time at the Olympics. A total of 1,788 athletes from 79 nations participated. Among several novelties was the location of the "Olympic village" on the campus of the University of Lausanne. The YOG was an opportunity to bring the academic and sports worlds closer together. The University of Lausanne collaborated with the IOC on various educational and scientific programmes for athletes and the public. Thus, in collaboration with IOC's Olympic Studies Centre and several academic institutions, the Institute of Sport Sciences (ISSUL) organised the congress "*Youth and winter sports*" https://wp.unil.ch/cyws20/program/ on January 7 and 8. It aimed to bring together sports scientists, coaches, and medics with an interest in winter sports, and around 200 people attended the congress.

Several points (not only the pre-COVID date!) made this congress very special:

1. Free access for all UNIL students and all athletes or staff registered for the YOG with the goal of fruitful exchanges between scientists and practitioners. The Olympic village was only 200 m from the congress location, and we were visited by elite coaches.
2. This congress was officially a component of the educational program of the YOG overviewed by UNIL.
3. This congress was multidisciplinary with key notes and parallel sections on both life sciences and social sciences. We received communications about physical preparation, physiology, biomechanics, sports medicine, rehabilitation, history, sociology, management, psychology, and teaching.

   The following world-class experts gave six key-note presentations:

   - Milena Parent (Canada)—Governance and legacy of the YOG
   - Hans-Christer Holmberg (Sweden)—Biomechanics and physiology in nordic skiing
   - Andrew Denning (USA)—History of the human–environment relationships in the Alps through the sport of skiing
   - Erich E. Muller (Austria)—Biomechanics and prevention of injuries in alpine Skiing
   - Oyvind Sandbakk (Norway)—Norwegian success in winter sports
   - Laurent Schmitt (France) – Martin Fourcade's physiological adaptations-—10 years of training and monitoring.

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4. This congress was not supported by a scientific society and was a one-shot organisation connected to the YOG.
5. The congress was supported by Frontiers in Sport and Active Living with the possibility for scientists to submit articles to the present Research Topic.

RESEARCH TOPIC "YOUTH AND WINTER SPORTS"

Though the Research Topic is multidisciplinary, which is in line with the content of the congress, only articles concerning exercise physiology, biomechanics, and nutrition have been published.

Four articles focused on biomechanical considerations in alpine skiing:

1. Pavailler et al. assessed the differences in glide time, ski edging, and plantar pressure distribution in national and regional cross-country skiers. The elite skiers exhibited better techniques, which is evidenced by the higher relative glide time induced by a larger body mass transfer above the ski particularly at the beginning of the gliding phase.
2. Nimmervoll, Çakmak et al. investigated the forces within the Alpine ski boots and reported that the location of the sensors is paramount for relevant data collection: the insole sensors located in the heel and front areas combined with the shaft sensors provide reliable data on forward and backward leanings.
3. Nimmervoll, Eckerstorfer et al. displayed a new method to release ski binding with an industrial robot. This method allows for the analysis of the respective forces and the release-retention behaviour of ski bindings.
4. Delhaye et al. investigated the kinetic and kinematic specificities of different line strategies (i.e., Z long straight line and sharper turns vs. S short straight line and long curved turns) in Giant slalom and the effects on the alpine skier performance and energy dissipation. Overall, these two strategies lead to similar energy dissipation characteristics, and the authors concluded that elite skiers need to possess a variety of these strategies.

Two articles assessed the talent development in youth cross-country skiers:

1. Zoppirolli et al. reported the changes in anthropometric and physiological characteristics of male and female young cross-country skiers. They showed that, during the late teenage period, high values and threshold levels of VO_{2max} appeared to be good indicators of further talent.
2. Wehrlin and Steiner similarly reported that early (16 and 19 years of age) physiological characteristics (i.e., high total haemoglobin mass expressed in g/kg) are relevant predictors of success at the senior level in endurance sports like cross-country skiing or triathlons.

Finally, this Research Topic includes three reviews (compression garments, injuries, and nutritional considerations) relevant to all winter sports:

1. Yang et al. reviewed 18 studies about the effects of compression garments on performance, drag, and vibrations in several winter sports.
2. Xu et al. reviewed 39 studies on injury factors in winter sports and provided much interesting information: The highest injury incidence was recorded in freestyle skiing, followed by alpine skiing and snowboarding. The most injured body parts were the knees (30%), head and face (12%), shoulders and collarbone (10%), and lower back (9%). The most common injury types were joint and ligament injury (41%), fracture and bone stress (24%), concussion (11%), and muscle/tendon injury (11%).
3. Hannon et al. provided an outstanding guideline on nutrition in youth winter sports athletes. Special considerations related to the environmental conditions as well as the maturation process in these athletes have been discussed, and energy, vitamin D, calcium, iron, and hydration have been analysed.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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REVIEW
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Effectiveness of Using Compression Garments in Winter Racing Sports: A Narrative Review

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Nowadays, compression garments (CGs) are widely used in winter racing sports, such as speed skating, short-track speed skating, alpine skiing, and cross-country skiing. However, the effect of wearing CGs on athletic performance in these specific sports is still not fully examined. Thus, the aim of this narrative review is to summarize the research and application of CGs in winter racing sports and to discuss how the CGs help athletes improve their performance in an integrative manner (i.e., physiology, aerodynamics, and biomechanics). A total of 18 experimental studies dedicated to CGs in winter racing sports were identified from the peer-review scientific literature. The main findings are as follows. (1) Currently, CG studies have mainly focused on drag reduction, metabolism, muscle function, strength performance, and fatigue recovery. (2) The results of most studies conducted in wind tunnels showed that, for cylindrical structures similar to the human body, clothing with rough surfaces can reduce air drag. Notably, the effect of CGs on drag reduction in real competition has not been fully explored in the literature. (3) Compression can reduce muscle vibrations at high impact and help athletes control the center of pressure movement, a function that is important for alpine skiing. Future studies are needed to improve current understanding of the effects of compression clothing microstructure on drag reduction and their stretching in different parts of the body. Furthermore, the design of experimental protocol must be consistent with those during the competition, thus providing a full discussion on energy metabolism, fatigue, and recovery affected by CGs.

Keywords: speed skating, alpine skiing, cross country skiing, air drag, muscle function, strength, fatigue, metabolism

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INTRODUCTION

In modern sports events, sport equipment is an essential factor for athletes to overcome their limits and achieve breakthroughs. Nowadays, high-tech compression garments (CGs) (e.g., compression clothes, shorts, and socks) are becoming increasingly popular among sports elites and enthusiasts. Meanwhile, the physiological benefits of CGs in enhancing athletic performance have been widely recognized, i.e., improvement of fatigue recovery (Brown et al., 2017), promotion of blood flow (Privett et al., 2010), regulation of blood lactate and creatine kinase levels (Kim et al., 2017), and the enhancement of muscle functions (e.g., reducing muscle vibrations and activation) (Broatch et al., 2019). Aside from the aforementioned advantages, CGs have also been commonly used and have shown potential benefits in winter racing sports (Sperlich et al., 2013; Chowdhury et al., 2015; Moon et al., 2016), including speed skating, short-track speed skating, alpine skiing, cross-country skiing, bobsleigh, luge, and skeleton. These broader applications can be attributed to the integrated aerodynamics and mechanical properties of the latest CGs.

In particular, the aerodynamic application of CGs is critical for winter racing sports. For example, speed skating (including short-track) generally reaches an average speed of 35–40 km/h (Brownlie and Kyle, 2012); meanwhile the average speed of alpine skiing, bobsleigh, and luge can exceed 100 km/h (McCradden and Cusimano, 2018). Therefore, the design principles of individualized CGs for each discipline have been set according to the peculiarity of aerodynamics (Supej and Holmberg, 2019). Furthermore, small differences in aerodynamic drag can exert a major impact on finishing time (Supej and Holmberg, 2019). Similar to dimpled golf balls, these racing CGs use common textured fabrics, and the structure could trip the wake turbulence flow to reduce drag. Chowdhury et al. (2015) reported a rough fiber structure of skating suits, which showed a significant positive effect on the air flow characteristics over the surface. In addition, bobsleigh, skeleton, and luge athletes use either their body posture or rudder to control the direction of their vehicles' slide on the ice track (Mosey, 2014; Colyer et al., 2018). Therefore, the primary task in those three events is to reduce the drag of the track and air by changing body posture and using proper clothing and equipment, thus increasing the transmission efficiency of the system (Peyre-Tartaruga and Coertjens, 2018). This can be achieved, for example, by covering the skin using CGs to reduce the drag area of the body (Spring et al., 1988). Collectively, the fabric surface design/materials of CGs can be regarded as an aerodynamically beneficial approach, which can help optimize the aerodynamic drag of racing sports to the greatest extent (Bardal and Reid, 2012).

On the one hand, in terms of mechanical properties, CGs can stabilize/support the underlying tissue by reducing the vibration of the soft tissue compartments (Sperlich et al., 2013). This can help mitigate exercise-induced discomfort and potentially reduce the energy expenditure, which largely depends on the pressure applied to the skin and musculature (MacRae et al., 2011). On the other hand, with respect to the energy production and muscle efficiency, CGs can provide multiple benefits, i.e., reducing muscle fatigue (Bringard et al., 2006), accelerating recovery of muscular power (Kraemer et al., 2010), and promoting the motor-unit activation coordination (Moon et al., 2016). Furthermore, CGs may optimize sports techniques; for example, the prediction of performance can be determined by the aforementioned parameters of energy production, efficiency, and technique with a power balance model (de Koning et al., 2005). Thus, these improved physiological and biomechanical characteristics brought on by the use of CGs are beneficial for enhancing athletes' performance in winter racing events (Supej et al., 2011).

The aim of this narrative review is to examine the effectiveness of using CGs in winter racing sports. We will begin by reviewing the drag reduction performance of CGs. Then, we will assess the effect of CGs on physiology and biomechanics. This will be followed by a review of how CGs influence fatigue recovery. Finally, we will identify gaps in our knowledge and provide suggestions for future directions. The overall aim of this paper is to summarize the research and application of CGs in winter racing sports and to discuss how the CGs help athletes improve their performance in an integrative manner (e.g., aerodynamics, physiology, and biomechanics).

LITERATURE SEARCH METHODOLOGY

While this review is narrative in nature, a systematic search was conducted via Web of Science, PubMed, and SPORT Discus (EBSCO) from inception to January 2020 in order to ensure that relevant studies were not overlooked. Articles were required to be peer-reviewed, in full text, and in English language. The keywords for the search were "speed skating," "bobsleigh," "luge," "skeleton," "alpine skiing," "cross-country skiing," "compression suits," "competition suits," "skinsuit," "compression garment," and "compression clothing." Search terms were combined by Boolean logic (AND, OR). Research articles were included if they (1) analyzed CGs for winter racing events and (2) were about sports science and sport medicine. Articles were excluded if they (1) were review articles, business reports, and official announcements; (2) were about cloth design, textile technology, and social sciences; and (3) had duplicate and ambiguous literature. The reference lists of all the articles retrieved were also manually searched for any relevant articles that were not identified electronically.

To date, there have been thousands of studies on pressure garments or CGs in various fields. Initial results were retrieved in more than 500 publications. The authors determined the exclusion criteria by reading titles and abstracts that fit the inclusion criteria, resulting in 112 articles. After reading the full texts of these articles, only 18 experimental studies were identified to be dedicated to CGs in winter racing sports (**Figure 1**). After simple classification and statistics, we found that these studies involved aerodynamics, biomechanics, and physiology. The studies were mostly focused on aerodynamic research on drag reduction (44%), metabolism (22%), muscle mechanics (28%), and fatigue recovery (6%) (**Figure 2**). In the current study, we did not systematically review these articles. However, we conducted a narrative review of the articles and combined their different aspects, such as integrative physiology and biomechanics.

FINDINGS

As shown in the searched results (**Table 1**), the effectiveness of using CGs in winter racing sports was from an integrative perspective, i.e., drag reduction, metabolism, muscle mechanics, and fatigue recovery. From the perspective of mechanical efficiency, two main aspects were proposed: the transmission/propulsive efficiency (drag reduction, joint

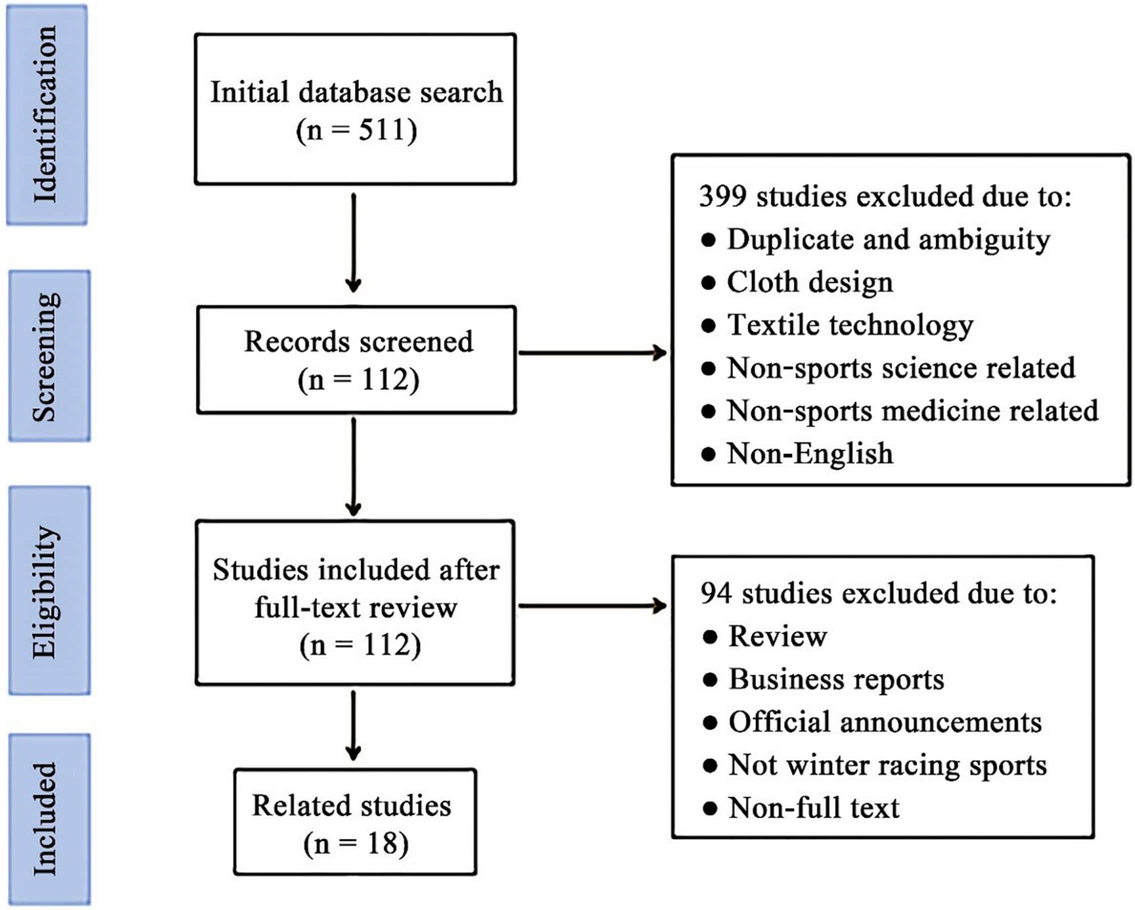

FIGURE 1 | Flow diagram of the literature selection process and the number of articles (n) after each stage.

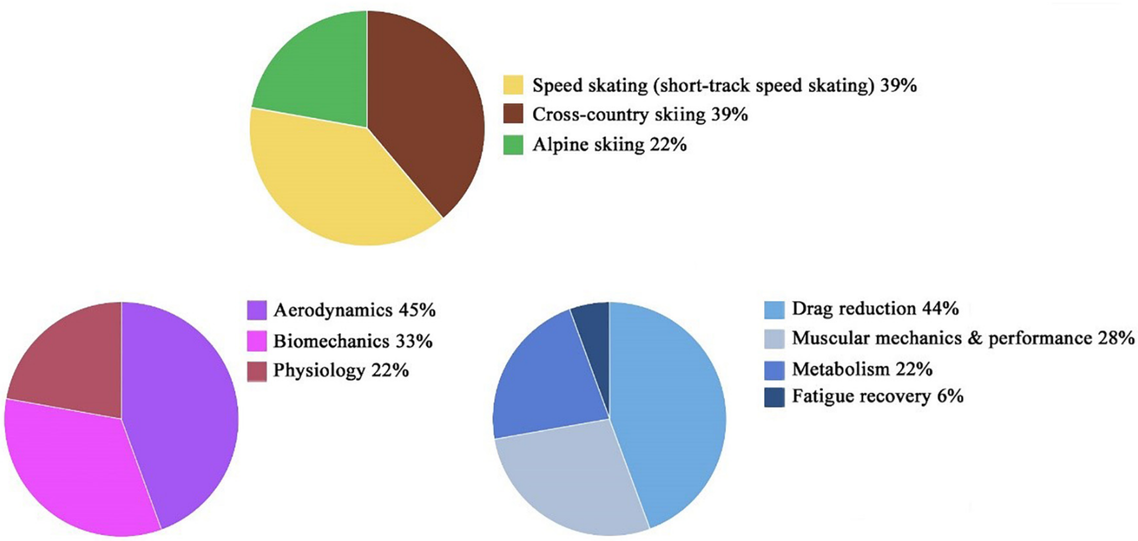

FIGURE 2 | Classification and proportion of research on CGs for winter racing sports.

TABLE 1 | List of studies on the effectiveness of using CGs in winter racing sports.

Author	Year	Population	Compression suit	Study design	Findings
Drag reduction (*n* = 8)					
Brownlie et al., 2004	2004	A mannequin model based on scale photographs from 15 elite sprinters and 16 speed skaters	Fitting samples of 39 stretch fabrics	(1) F_D and air velocity were measured with wind tunnel tests. (2) C_D and Re were used to characterize the ability of the various fabrics to generate FT.	Compared with the bare leg, the leg model covered with the best-matched fabric reduced F_D and C_D by 20.2 and 40%, respectively.
Kuper and Sterken, 2008	2008	Full set of the speed skating results of the 2002 Olympic Winter Games	Five branded skating suits	The average skating speeds of the 500–10000 events were modeled with a pooled linear regression. The two-stage generalized least squares (instrumental variable) of regression model are the home advantage dummy variable, age, length, squared length, and weight of the athletes.	Once corrected for selection bias, none of the suits outperformed the others.
Sætran and Oggiano, 2008	2008	A mannequin was used to simulate the average posture of 1500 m speed skating athletes.	Six suits with fabrics of different roughness for lower legs, upper legs, trunk, arms head, and arms.	The speed of each discipline was simulated for women and men, and air drag was measured using the sensors placed at the joints.	(1) The final time difference of about 3 s was estimated in the suits with different surfaces. (2) Legs were the most sensitive area in fabric selection.
Oggiano and Sætran, 2010	2010	A mannequin was used to simulate the posture of cross-country skiing athletes.	Six suits with three kinds of roughness and two kinds of thickness.	Velocity varied from 15 m/s to 25 m/s with 1 m/s interval. Force balance in the base plate measured the air drag.	Ski suits with rough fabrics reduced air drag by 10%.
Oggiano et al., 2012	2012	A cylinder model simulated the limbs.	Three cross-country suits with rough fabrics were used, which were stretched at 9, 23, 43, and 63%.	The range of test velocity was 0–16 m/s. Force balance in the base plate measured the air drag.	A higher strain “smooths” out the fabric surface, moving the critical speed closer to the speed for a smooth one.
Brownlie and Kyle, 2012	2012	A mannequin of a competitive speed skater was used.	Six speed skating suits used in the 2002, 2006, and 2010 Winter Olympic Games.	(1) F_D measurements were performed with wind tunnel tests in the air velocity range of 12–15.6 m/s. (2) The difference in pre-Olympic to Olympic performance based on skating suits was compared.	(1) SWIFTSkin was observed to provide the greatest reduction in F_D by 13.3%. (2) Skaters with SWIFTSkin suit exceeded their previous personal best performance by 1.03%. (3) Skaters clad in other speed suits exhibited minor differences in performances.
Bardal and Reid, 2012	2012	The cylinder models with three different diameters were used to model the calf, thigh, and upper arm	With stretch of 25 and 42%, the fabrics with three different roughness levels were compared.	The fabric performance under stretching were tested in the wind tunnel at an air velocity equivalent to 17.5 m/s at typical race environmental conditions	The transition speed was affected when the absolute stretching of the fabrics is increased from 25 to 42%
Chowdhury et al., 2015	2015	A standard cylinder was used with a 110 mm diameter and 200 mm length	Four commercially made skinsuits from different manufacturers were compared.	Wind tunnel tests were conducted at a range of air velocities (20–120 km/h with an increment of 10 km/h). Electron microscopic analysis was used to observe the fabric properties of the skinsuits.	(1) Compared with the bare cylinder, all skinsuit fabrics can gain aerodynamic advantages. (2) Smooth surface for streamlined bodies can reduce the drag efficiently. (3) An increase in surface roughness can reduce the drag for the quasi-cylinder.

(Continued)

TABLE 1 | Continued

Author	Year	Population	Compression suit	Study design	Findings
Metabolism, muscle function, and mechanical performance (*n* = 9)					
Sperlich and Holmberg, 2011	2011	Six elite cross-country skiers (age: 29 ± 6 years; height: 174 ± 10 cm; body mass: 67.9 ± 10.7 kg)	2009 and 2010 racing suits	(1) Tested at 12 km/h at 5° inclination; 11 km/h at 6° inclination; and 12 km/h at 8° inclination with roller skating for 6 min. (2) Tested oxygen uptake, minute ventilation, HR, skin, core temperature, etc.	(1) Oxygen uptake, minute ventilation, RER, HR, etc. were all lower with the 2010 skiing suit. (2) Average skin and core temperature were lower with the 2010 skiing suit.
Sandsund et al., 2012	2012	Nine male endurance athletes (age: 25 ± 3 years; height: 183 ± 7 cm; body mass: 78.6 ± 7.4 kg; body fat: 11.9 ± 2.3%; VO_{2max}: 5.6 ± 0.4 · min^{-1})	With one-piece cross-country skiing suits	(1) Standard running tests were performed at six ambient temperatures (–14, –9, –4, 1, 10, and 20°C) with an air velocity of 5 m/s. (2) Skin and core temperatures, VO_{2max}, TTE, running economy (HR and VO_2), and running speed at LT were measured.	(1) Skin temperature decreased significantly with reduced ambient temperatures, and core temperature increased during all conditions. (2) Optimal endurance performance with cross-country skiing suit was found at –4 and 1°C.
Sperlich et al., 2013	2013	Twelve elite male alpine skiers (age: 26 ± 4 years; body mass: 80 ± 5 kg)	Three compression shorts in different pressures (0, 20, and 40 mmHg)	(1) Simulated actual alpine skiing posture, vibration and load for 3 min. (2) Tested EMG activity, cardiopulmonary data, hemoglobin, oxygenation of VL, muscle vibration, blood lactate concentration, RPE, joint angle, maximal isometric knee flexion, jumping height, and balance ability before, during, and after trials.	(1) Knee flexion and muscle vibration decreased with increasing pressure. (2) Percentage of muscle activities (pre–post): TA (20.2–28.9%), gastrocnemius medial (4.9–15.1%), RF (9.6–23.5%), and VM (13.1–13.7%). (3) Hemoglobin without compression was lower than 20 or 40 mmHg compression.
Born et al., 2014	2014	Ten German speed skaters from the national team (age: 23 ± 7 years; height: 173 ± 10 cm; body mass: 68.2 ± 13.9 kg; peak oxygen uptake: 58 ± 5.2 mL · kg^{-1} · min^{-1})	With or without compression shorts	(1) Simulated the 3000 m speed skating competition. (2) Tested the lateral femoral muscle oxygenation and blood volume with near-infrared (IR) spectroscopy. (3) Tested the oxygen uptake, ventilation, HR, speed, etc.	(1) Oxygenation in the vastus lateralis was asymmetrical. (2) Leg compression did not affect oxygenation asymmetry and other parameters.
Sperlich et al., 2014	2014	Ten elite long-distance cross-country skiers (age: 25 ± 4 years; height: 180 ± 4 cm; body mass: 74.6 ± 3.2 kg)	With or without long-sleeved CGs	(1) Simulated 3 min of double-poling sprints three times. (2) Tested the PO, HR, RER, oxygen uptake, carbon dioxide production, and stroke volume. (3) Tested the blood volume of the triceps brachii with near-IR spectroscopy.	No effect on all parameters.
Wiggen et al., 2016	2016	Thirteen highly trained male cross-country skiers (age: 23 ± 2 years; height: 180 ± 5 cm; body mass: 76.5 ± 4.7 kg; body fat: 9.8 ± 2.0%)	With standard cross-country ski racing suits	(1) At –15 and –6°C, performed Sub1, a self-paced 20-min performance tests, Sub2, and incremental tests to exhaustion. (2) Measured skin and core temperatures, PO, and respiratory variables.	(1) Skin and core temperatures were more reduced with standard racing suits, and average PO was 5% lower in the first 8 min of the performance test at –15°C. (2) From Sub1 to Sub2, the double-poling economy decreased by 3.7% larger at –15°C.

(Continued)

TABLE 1 | Continued

Author	Year	Population	Compression suit	Study design	Findings
Moon et al., 2016	2016	Ten students (age: 20 ± 0.89 years; height: 172 ± 4.9 cm; body weight: 66.7 ± 10.9 kg; 6 male, 4 female) in a physical exercise-related major	Fabric speed skating suits with three compression levels (0, 9, and 18% downsize)	(1) Surface electromyography test was used to investigate the activation of the RF. (2) The isokinetic test and Wingate test were used to investigate the maximum anaerobic power.	(1) The RF activity was significantly lower at 9% compression than at 0% compression. (2) The mean power and peak torque showed no significant differences in the three compression levels, except the flexion power in 18% compression.
Decker et al., 2016	2016	Nine collegiate alpine ski racers	With DCP or SCP tights	Peak GRF, maximum AP COP, minimum ML COP, COP area, and COP velocity were measured.	(1) During the DCP condition, peak ground reaction force decreased by 9%, the COP was more anterior and medial, and the COP velocity was 14% lower. (2) During the DCP condition, the dynamic balance was improved.
Simons et al., 2016	2016	Nine collegiate alpine ski racers	With DCP or SCP tights	(1) The VL, RF, BF, and GM muscle EMG amplitudes were measured. (2)Average ankle, knee, and hip positions and turn durations were calculated	(1) During the DCP condition, the hip and knee position was more flexed. (2) During the DCP conditions, VL, RF and GM muscle activations were reduced.
Fatigue recovery (*n* = 1)					
Govus et al., 2018	2018	Thirty-two Swedish national team skiers (18 males, 14 females)	Commercially available, moderate-pressure, upper- and lower-body CGs	(1) Skiers were randomly assigned to compression garments (*n* = 11), neuromuscular electrical stimulation (*n* = 11), or control group (*n* = 10). (2) CK, urea, CMJ height, and perceived muscle pain were measured before and 8, 20, 44, and 68 h after competition.	Neither CGs nor neuromuscular electrical stimulation promoted physiological or perceptual recovery compared with CON.

F_D, drag force; C_D, non-dimensional drag coefficient; Re, Reynolds numbers; FT, flow transition; HR, heart rate; VO_{2max}, maximal oxygen consumption; VO_2, oxygen consumption; TTE, running time to exhaustion; LT, lactate threshold; EMG, electromyography; RPE, rating of perceived exertion; CG, compression garment; PO, power output; RER, respiratory exchange ratio; Sub1, a 5-min submaximal test; Sub2, a second 5-min submaximal test; DCP, directional compression; SCP, standard compression; GRF, ground reaction force; AP, anterior-posterior; ML, medial-lateral; COP, center of pressure; VL, vastus lateralis; VM, vastus medial; RF, rectus femoris; BF, biceps femoris; GM, gluteus medius; TA, tibialis anterior; LF, lateral femoral; CK, creatine kinase; CMJ, countermovement jump.

stability, etc.) and the muscle efficiency (muscle fatigue, motor-unit activation coordination, etc.). Specifically, in the drag reduction functions, wind tunnel experiments were usually conducted according to the speed, posture, and anthropometry in various events. The majority of studies have shown that CGs with appropriate rough surfaces can reduce air drag (Brownlie et al., 2004; Oggiano and Sætran, 2010; Bardal and Reid, 2012). Meanwhile, CGs bring about benefits in physiology and biomechanics by applying compression to the skin and musculature, which can be achieved through the improvement of metabolism (Sperlich and Holmberg, 2011), the reduced muscle vibrations at high impact (Sperlich et al., 2013), and the improvement of muscle function (Moon et al., 2016). However, the number of studies on winter racing sports is not as many as those on general sports, and the fundamentals of the theory have yet to be fully explored.

Air Drag Reduction

The mechanical energy fluctuations caused by the collision with the external environment during movement leads to changes in the transmission efficiency (Peyre-Tartaruga and Coertjens, 2018). Reduced air drag, in turn, reduces the loss of total mechanical work (Supej et al., 2013). Hence, properly designed CGs with drag reduction feature provide less drag (Supej and Holmberg, 2019). In aerodynamics, the air drag reduction of materials was represented by the drag coefficient (C_D). Air drag (D) can be represented as (Oggiano and Sætran, 2010; Chowdhury et al., 2015)

$$D = \frac{1}{2} C_D \rho A v^2,$$

where ρ is the air density, v is the air velocity, and A is the frontal area of the object. Considering that the human limbs are quasi-cylindrical, the standard cylindrical methodology (Chowdhury et al., 2015) is currently used to quantify the aerodynamic drag on each suit fabric. In 2004, researchers reported a testing of speed skating suit (Brownlie et al., 2004). Using a mannequin model based on anthropometric data from 15 elite sprinters and 16 speed skaters, they tested CGs made from a fitting sample of 39 stretch fabrics. Their results showed that the best-matched fabric reduced air drag by 20.2%. Meanwhile, Oggiano and colleagues conducted a series of studies on the drag reduction performance of CGs by using several parameters, such as position, material, and the stretch of different fabrics (**Table 1**; Sætran and Oggiano, 2008; Oggiano and Sætran, 2010; Oggiano et al., 2012). Then, a wind tunnel experiment was conducted with a mannequin model based on the average posture of 1500 m speed skating competitors (Sætran and Oggiano, 2008). That study also compared the air drag reduction of fabrics on different body segments, including lower legs, upper legs, trunk, head and arms. On the basis of various parameters (e.g., frontal area and angle), they found that the thighs were the most sensitive area in air drag reduction; mainly, the thighs were perpendicular to the flow with a large frontal area and skin stretching range during movements (Sætran and Oggiano, 2008). Another study tested cross-country ski racing suits and found that rough fabrics could reduce air drag by 10% (Oggiano and Sætran, 2010). Similar to the results of Chowdhury et al. (2015), the C_D of the optimal rough fabrics decreased from 0.64 to 0.49 at air velocities of 50–60 km/h on the cylinder model. Considering the surface deformation due to strain after wearing CGs, Oggiano et al. (2012) investigated the air drag reduction of fabrics with different strains. They found that, as the air velocity increased, C_D was significantly reduced (without values) when reaching the critical velocity (the transition to turbulent); furthermore, with the increase of strain, the critical velocity of rough textile (63% stretched) was closer to smooth textile (23% stretched). That is, a higher strain "smoothens out" the fabric surface and changes the C_D.

The cutting and stitching of suits and other structures have also been shown to be beneficial to drag reduction. For example, the skin suit aligned with the seams corresponding with the air flow direction or were placed in the leeward direction to further reduce air drag (Kuper and Sterken, 2008). Low friction panels were also set under each arm and on the right inner thigh to reduce friction caused by arm swing and pushing off (Kuper and Sterken, 2008). Another skin suit (Braghin et al., 2016) developed by a Dutch company adopted a full-body skating suit design with a "skate strip" (i.e., a smooth rubber material on the head and thighs). Meanwhile, a Japanese company developed new speed skating suits, which reduced turbulence through spiral silicone strips on the thighs and lower arms (Braghin et al., 2016). Researchers tested and modified the different shapes, sizes, and placements of those strips.

Current studies suggest that the air drag reduction mechanism includes the following: (1) theoretically, the remarkable drag reduction property is beneficial to the performance. This can be explained from the energy and efficiency perspective: transmission efficiency is equal to the total mechanical work (W_{tot}) divided by the positive work produced by the muscle (Peyre-Tartaruga and Coertjens, 2018). Wearing CGs with drag reduction helps reduce W_{tot} loss and thus improve transmission efficiency (Supej et al., 2013); (2) a rough surface changes the boundary layer of the cylinder transition from laminar to turbulent in the wake region to reduce pressure drag (Chowdhury et al., 2015), and (3) drag-reducing structures in specific segments can further reduce air drag. However, most studies were laboratory-controlled experiments. The drag reduction effects of CGs in actual competitions remained largely unexplored.

Metabolism, Muscle Function, and Mechanical Performance

Currently, the main candidate parameters to improve the performance in winter sports disciplines are muscle function, metabolism, and mechanical performance (Hooper et al., 2015; Šambaher et al., 2016; Smale et al., 2018; Hintzy et al., 2019). The primary function of the muscles during locomotion is to produce positive mechanical work. Under the same metabolic energy consumption, the stronger ability to produce positive mechanical work, the higher the muscle efficiency (Peyre-Tartaruga and Coertjens, 2018). The use of CGs seems to provide benefits from these aspects.

Long-distance events in cross-country skiing and speed skating require endurance (Stöggl et al., 2018). Sperlich and colleagues conducted a series of studies (**Table 1**; Sperlich and Holmberg, 2011; Sperlich et al., 2013, 2014) wherein the physiology of elite cross-country skiers with compression suits was discussed. The subjects wore new (79% polyester, 18% polyurethane, and 3% carbon fabric) and old (80% polyester, 20% elastane) full-body suits. Lower values were found in oxygen uptake, minute ventilation, respiratory exchange rate (RER), heart rate (HR), skin, and core temperature with the new suits (Sperlich and Holmberg, 2011). The authors argued that wearing new suits, with their lighter weight and better moisture-wicking, was more economical for cross-country skiing. The team likewise tested the effect with or without long-sleeve CGs on double-poling sprints (Sperlich et al., 2014). The results showed that compression had no effect on power output, cardiopulmonary parameters, tissue saturation, and blood volume. These findings are consistent with those reported by a previous study on compression shorts for speed skaters (Born et al., 2014).

In terms of muscle function and mechanical performance, researchers have proven that CGs reduce soft tissue vibration (Doan et al., 2003; Hintzy et al., 2019). Alpine skiing can reach top speeds of 140 km/h (Bardal and Reid, 2012) and places high demands on turning and jumping technique for skiers (Jordan et al., 2018). Optimized CGs are required to reduce muscle vibration, especially for sports with high speed and impact.

Sperlich et al. (2013) simulated vibration and load in alpine skiing and found that high compression increased knee flexion and decreased muscle vibration and perceived exertion. Furthermore, the EMG of gastrocnemius medialis, rectus femoris, and vastus medialis increased with compression condition. Inconsistent with the aforementioned findings, Moon et al. (2016) reported that leg compression reduced the activation of the rectus femoris in isokinetic tests but had no significant effect on knee extension strength. However, direct comparisons of the findings between these two studies are not appropriate due to the different types of exercise (continuous passive vibrations vs. isokinetic leg extension/flexion) and external pressures adopted (0, 20, and 40 mmHg vs. 0, 9, and 18% compression) Fu et al. (2012, 2015) conducted a series of research on leg compression by testing different muscle contractions (i.e., isometric, isokinetic, and isotonic) and muscle activations for athletes. Their results showed that, while compression shorts did not affect muscle strength acutely, it did reduce the EMG activities and maintained similar power output during repetitive muscle contractions. These results are supported by a recent study from Broatch et al. (2019). Thus, we can speculate that reduced motor unit activation might represent a lower metabolic cost at the molecular level. Using less metabolic cost to maintain the same power output potentially implies higher muscle efficiency (Peyre-Tartaruga and Coertjens, 2018). This proposes another rationale behind the benefits of CGs.

In addition, most researchers held that CGs affected proprioception to achieve optimize performance (Doan et al., 2003; deBritto et al., 2016; Zamporri and Aguinaldo, 2018). Decker et al. (2016) investigated how compression shorts influenced turning direction in alpine skiing by testing the foot pressure characteristics. Their results showed that peak ground reaction force decreased by 9%, the center of pressure (COP) was more anterior, and the COP velocity was 14% lower, all of which demonstrated that leg compression improved dynamic balance. Simons et al. (2016) also analyzed the kinematics and EMG activities of alpine skiing athletes with CGs by performing the experiment in a race simulation. They found that, with compression shorts, the knee and hip flexion increased by 3 and 5%, respectively, and the average vastus lateralis, rectus femoris, and gluteus medius activations decreased by 17, 17, and 26%, respectively. Notably, they first measured the kinematic parameters with inertial measurement units (IMUs) in CGs for winter racing sports. Recently, an image processing system and the IMUs were used for outdoor motion capture (Kruk and Reijne, 2018), specifically for sports with high velocity and huge capture volume. The biomechanical characteristics of winter sports with CGs were further investigated with the help of those methods.

Fatigue Recovery

Fatigue recovery is crucial for the performance in training and competition for both short- (500 m short-track speed skating) and long-distance (50 km for men and 20 km for women in cross-country skiing) events. Accelerated recovery of energetic substrates can help improve the efficiency of phosphorylative coupling and further enhance muscle efficiency during the movement (Peyre-Tartaruga and Coertjens, 2018). Dealing with fatigue during a match and the recovery after the match are both vital to the performance of athletes. Research have proven that CGs promote fatigue recovery after exercise (Kim et al., 2017; Machado et al., 2018; Nguyen et al., 2019; Pérez et al., 2019).

Govus et al. (2018) tested 32 elite cross-country skiers for blood lactate, creatine kinase, urea, countermovement jumping (CMJ) height, and perceived muscle pain before and after competition. Participants were randomly divided into the CG group (n = 11), the neuromuscular electrical stimulation group (n = 11), and the control group (n = 10). The parameters were tested before and after the competition at 8, 20, 44, and 68 h. Compared with the control group, neither CGs nor neuromuscular electrical stimulation promoted the recovery of blood biomarkers, CMJ height, or perceived muscle pain after competition.

Some limitations in the present study were caused by ecological factors, including dietary habits, intensity difference in experiment and training and competition. Currently, the relevance of the physiology and biomechanics in fatigue and recovery remains unclear. CGs reduce muscle vibration and activation without affecting performance (Fu et al., 2012, 2015; Broatch et al., 2019). Researchers suggested that, for forms of movements that require frequent and repetitive muscle contractions, reduced muscle activation can improve contraction efficiency and decrease energy loss and muscle fatigue. The muscle vibrations and proprioception changes caused by CGs may alter the kinematics of movement, and the characteristics of kinematics are related to the economy and efficiency of motion or the generation of fatigue (Engel et al., 2016). Therefore, there is still a lack of sensitive biomechanical parameters to evaluate CGs for winter sports.

With respect to physiology, CGs have effects on strength promotion, power recovery and reduction of delayed onset of muscle soreness (DOMS) (Bottaro et al., 2011; deGlanville and Hamlin, 2012; Goto and Morishima, 2014; Molly and Shelby, 2018). Furthermore, CGs promote the recovery of exercise-induced muscle damage (Kraemer et al., 2001; Arbabi, 2015), reduced lactate (Duffield et al., 2010; Saulo et al., 2015) and increased tissue saturation (Dermont et al., 2015). Despite the inconsistent results (Bringard et al., 2006; Stickford et al., 2015) regarding the effects of CGs on fatigue performance and economy of motion, this may be caused by the heterogeneity of the test procedures, e.g., the difference of types and levels of compression (Pérez et al., 2019).

Furthermore, different sports have different techniques and tactical characteristics that indicate different demands on CGs for fatigue recovery. Thus, the use of CGs for specific winter sports is worthy of further exploration and should not be limited to speed skating, cross-country skiing, and alpine skiing. Moreover, systematic reviews of the role of compression in major physiological aspects in winter racing sports, e.g., fatigue recovery and muscle function enhancement, are warranted.

CONCLUSION

Winter sports have increasingly relied on professional equipment, such as CGs. The main points held by this narrative review include the following. (1) Currently, CG studies in winter racing sports have mainly focused on drag reduction, metabolism, muscle function, strength performance, and fatigue recovery. (2) The results of most studies conducted in wind tunnels showed that, for cylindrical structures similar to the human body, clothing with rough surfaces can reduce air drag. Notably, the drag reduction effect of CGs in real competition have yet to be fully explored. (3) Compression can reduce muscle vibrations at high impact and help athletes control the COP movement during competition, a function that is important for alpine skiing. However, it is noteworthy that, for the effects of CGs, the number of studies on winter racing sports is not as many as those on general sports.

Future studies could focus on the following subtopics: (1) investigating the effects of clothing microstructure on drag reduction and their stretching in different parts of the body, specifically on which area is most sensitive to reducing air drag; (2) ensuring that the temperature, humidity, and speed during experimental research are consistent with those during the competition; and (3) providing a full discussion on energy metabolism, fatigue, and recovery affected by CGs. These effects cannot be ignored, because long-distance events are carried out in harsh environments and changing tracks.

AUTHOR'S NOTE

This is a narrative review of past studies that are relevant to the topic of interest.

AUTHOR CONTRIBUTIONS

WF contributed to the conceptualization, project administration, and funding acquisition. CY and YX contributed to the literature retrieval and the preparation writing of the original draft preparation. CY, YX, YY, and SX contributed to the literature screening. YX contributed to the data curation. WF, CY, YX, YY, and SX contributed to the review and editing. All authors contributed to the article and approved the submitted version.

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Glide Time Relates to Mediolateral Plantar Pressure Distribution Rather Than Ski Edging in Ski Skating

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The purpose of this study was (i) to assess the differences in relative glide time and both ski edging angle and plantar pressure mediolateral distribution in skiers of different levels and (ii) to further investigate the relationships between the aforementioned variables. Twelve male cross-country skiers (6 national and 6 regional level) skied at 4.2 m s^{-1} on a 2.5° uphill snow track using the V2 technique. The relative glide time (in percentage of contact time) and mediolateral plantar pressure distribution variables (asymmetry index, ASI) were derived from pressure insole measurements. Ski edging angle variables were calculated from an Inertial Measurement Unit placed on the ski. Minimum, maximum, mean, and range of both ASI and ski edging angle were computed over the gliding phase, giving information about the beginning, end, and throughout the gliding phase. Relative glide time was significantly higher, and minimum and mean ASI were significantly lower in the national- than in the regional-level skiers. Relative glide time was strongly negatively correlated to minimum ASI (i.e., plantar pressure mostly on the foot lateral side at the beginning of gliding phase) and strongly positively correlated to ASI range. These results may reflect a larger body mass transfer above the ski from the beginning of the gliding phase to increase gliding, especially in the national-level skiers. Ski edging angle seems less relevant to discriminate skiers' level of performance. These results have direct consequences on how technique must be taught to young cross-country skiers.

Keywords: cross-country skiing, performance, asymmetry index, inertial measurement unit, submaximal speed, V2 technique

INTRODUCTION

Cross-country skiing skating style comprises different techniques between which skiers change according to speed and slope (Nilsson et al., 2004). Among those technique, V2 (poling phase for every ski thrust, also called G3) has become increasingly used by skiers during competitions, especially in sprint races (Andersson et al., 2010). Several studies examined the cycle characteristics that determine V2 skiing speed and agreed that a strong relationship exists between speed and cycle length (Bilodeau et al., 1992, 1996; Smith, 1992; Boulay et al., 1994; Sandbakk et al., 2011). Elite skiers achieve long cycle lengths with short but strong propulsive phases and long gliding phases (Bilodeau et al., 1992; Stöggl et al., 2008), i.e., low duty cycles. Interestingly, proportional increases of maximal skiing speed, cycle length and absolute gliding phase duration were found in elite skiers during their inter-season preparation (Losnegard et al., 2017). The authors interpreted these changes as improvements in skiers' global fitness and balance, and they associated them to "*possibly reduced friction on snow because of a flatter oriented ski.*" Indeed, the ski flatness to the snow surface (ski edging angle) can influence the gliding phase as it affects ski penetration into snow surface layers (Smith, 2000), explaining practical recommendations from coaches to athletes to reduce friction coefficient by keeping the ski flat during gliding. A recent study showed that peak velocity reached during an incremental test was correlated to a flat or even negative ski edging angle at initial ski–snow contact, i.e., contact with the external edge (Stöggl and Holmberg, 2015). Yet, an older study found that ski edging angle was not significantly related to skiing performance (appraised by cycle velocity and race velocity) during the 50-km Olympic race (Smith and Heagy, 1994). In this study, none of the skiers maintained the ski flat during the gliding phase. In both these studies, ski edging angle was estimated through shank angle relative to vertical, which could bias the results due to possible movements occurring at the ankle in the frontal plane. A measurement taken directly on the ski would improve accuracy, as allowed by modern inertial measurement units (Sakurai et al., 2016).

However, the relevance of studying ski edging angle to improve ski–snow interaction during the gliding phase can be questioned. Ski edging angle only characterizes ski positioning on the snow, which may not be the best variable to assess ski–snow interaction quality and so affecting gliding. Since friction force depends directly on normal force, snow drag during the gliding phase could also be affected by the mediolateral distribution of the load (i.e., skier's body weight) on the ski. Consequently, analyzing mediolateral plantar pressure distribution could be important to better understand the foot–ski–snow interaction during the gliding phase. Indeed, the distribution may provide relevant information about how the skier's mass is transferred above the ski during the gliding phase. Center of pressure patterns during a skating cycle has previously been studied in elite skiers (Smith, 1992; Stöggl et al., 2011). These two studies showed that the center of pressure was approximately centered in the mediolateral dimension during the gliding phase, which implies a homogeneous pressure distribution between the medial and lateral plantar foot area. This homogeneous pressure distribution in the mediolateral dimension would allow skiers to spread the load on the entire foot, and subsequently on the ski, which could reduce snow drag and thus minimize the deceleration during the gliding phase. Even if ski edging has been intuitively associated to a more homogeneous distribution of pressure under the ski, the latter may be better and more directly characterized by mediolateral plantar pressure distribution. Therefore, the main objective of the present study was to determine the effect of the skiers' level of performance on relative glide time and both ski edging angle and plantar pressure mediolateral distribution during on-snow V2 skiing. To further support the association between relative glide time and ski edging angle and plantar pressure mediolateral distribution, the relationships between these variables were assessed using a correlation analysis. It was hypothesized that the higher-level skiers would demonstrate longer relative gliding phases and more homogeneous plantar pressure distributions in the mediolateral dimension rather than flatter ski edging angles.

MATERIALS AND METHODS

Participants

Twelve male cross-country skiers volunteered to participate in the study. All of them reported (i) wearing cross-country skiing boots size 8.5 UK and (ii) having taken part in at least one competition in the two preceding years. They were arranged into a national-level group and a regional-level group based on their score in the ranking system of the French Ski Federation. Selected characteristics of the participants in each group are presented in **Table 1**. As expected, skiers in the national-level group had a significantly better French Ski Federation Score and a higher weekly cross-country skiing training volume than the regional-level skiers, with respectively very large and large associated effect sizes.

Experimental Protocol

Testing was conducted on snow on a freshly groomed, straight skating track. The track was 70 m long with 3 m of positive elevation, resulting in a constant slope of 2.5°. The first 25 m were used for acceleration, and the following 45 m served as measurement area. The participants were instructed to use the V2 skating technique (also called G3, Nilsson et al., 2004), which consists in a symmetrical and synchronous pole push at each leg push off (Bilodeau et al., 1992). Prior to the experiment, a skilled cross-country skier was trained to maintain a 4.2 m s^{-1} speed through the measurement area. During the tests, this skier was placed ahead the participants to fix the speed, and participants were instructed to follow him at about 10 m and to keep this distance constant during the measurements. This speed was chosen to be a representative slow pace training speed (as confirmed by the participants' feedbacks), in order to focus on technical abilities rather than physiological or force production capacities. Actual average speeds over the 45-m measurement

TABLE 1 | Selected characteristics (mean ± SD) of the participants in the two groups.

	National	Regional	*P*	Effect size
N	6	6	–	–
Age (years)	28.0 ± 6.2	31.3 ± 8.9	0.47	0.47 small
Body mass (kg)	69.2 ± 4.1	70.3 ± 2.3	0.55	0.36 small
Height (cm)	178.3 ± 3.4	180.5 ± 2.7	0.26	0.79 moderate
Pole length (% of height)	89.7 ± 1.0	88.9 ± 1.2	0.26	0.79 moderate
Weekly cross-country skiing volume (h)	14.3 ± 5.9	8.6 ± 2.5	**0.05**	1.38 large
French ski federation score (points)	52.5 ± 35.6	137.8 ± 32.2	**0.01**	2.75 very large

Bold P-values indicate significant difference between the two groups.

area were controlled for each participant (4.4 ± 0.3 m s^{-1}, coefficient of variation: 6.5%). Each participant skied the entire track twice: the first trial for habituation to the target speed and the second one for analysis. Testing of each participant was completed within 1 h. The testing of all participants was performed during a period of 6 days during which weather conditions were stable (clear skies). The ski track was prepared every morning by the same operator.

All participants used the same pair of skating shoes (S-Lab Skate Pro, Salomon, Annecy, France), size 8.5 UK, and the same pair of skating skis (S-Lab Equipe 10 Skate, Salomon) mounted with a binding of SNS standard (SNS Pilot Equipe Skate, Salomon). Hygienic insoles were removed from the shoes and replaced by the plantar pressure insoles (PEDAR System, Novel Electronics, Munich, Germany). The participants used their own poles for the tests and carried a small backpack (XA 10+3, Salomon) to transport the acquisition systems (total mass: 1.2 kg). The participants did not report any inconvenience caused by the backpack during skiing. Before each test session, skis were cleaned, prepared with a racing wax (Maplus 40–60 SM Base Solid, Briko, Milan, Italy), and brushed.

Measurements

Plantar pressures were measured using a Pedar mobile system (Novel GmbH, Munich, Germany). This system sampled at 50 Hz and consisted of two pressure insoles (size 8.5 UK) covered with 99 sensors and a data logger with internal flash memory. The calibration of the insoles was set according to the manufacturer's guidelines before each data recording. As the V2 technique employed is symmetrical, and as ski edging angle was recorded on the right side, only data from the right insole were used for further analysis. The ski edging angle was measured as the ski angle around its longitudinal axis. It was recorded with one Inertial Measurement Unit (MT9, Xsens Technologies B.V., Enschede, Netherlands) solidly fixed with reclosable fastener (3M Dual Lock, 3M, Saint Paul, Minnesota, United States) on the right ski about 2 cm ahead the binding, with the *X* axis aligned with the ski longitudinal axis. The Xsens system sampled at 50 Hz and included a data logger linked by cables to a notebook (Latitude 2100, Dell, Round Rock, USA). Inertial Measurement Units are now widely used in cross-country skiing movement analysis (Myklebust and Nunes, 2011; Marsland et al., 2012; Tjønnås et al., 2019) and were proven to be accurate and reliable in gliding movement analysis (Krüger and Edelmann-Nusser, 2010). The notebook and the Xsens and Pedar acquisition systems were placed in the backpack carried by the participants. The synchronization between both the Pedar and Xsens systems was achieved by striking the right foot and ski on the ground at the beginning of each trial.

Data Reduction and Analysis

A custom designed mask was applied to the pressure insole data in order to split the total foot area into a medial and a lateral area, resulting in two areas having the same surface (74.7 cm²). The average pressure over the total masked foot area was calculated and used to determine cycle characteristics. One step was defined as the period when the ski was in contact with the ground and was composed of a gliding phase followed by a propulsion phase. The gliding phase was defined as in Stöggl et al. (2011); i.e., it started with the placing of the ski on the ground (increase in plantar pressure), leading to a first peak in the total pressure curve, and ended when the total pressure reached a local minimum around midstep. Only data from this gliding phase were used for further analysis.

The relative glide time was expressed relatively to the ski–snow contact duration (T_{glide} in %).

To appraise plantar pressure distribution between the medial and the lateral area, an asymmetry index (ASI, in %) was calculated at each instant of the gliding phase with the following equation (Robinson et al., 1987).

$$ASI = \frac{P_{medial} - P_{lateral}}{(P_{medial} + P_{lateral})} \times 100\ \%$$

where P_{medial} was the average pressure over the medial area and $P_{lateral}$ was the average pressure over the lateral area. ASI values ranged from −100 to 100%: a negative value indicated a higher pressure on the lateral area, a positive value indicated a higher pressure on the medial area, and an ASI equal to 0 reflected an equally distributed mediolateral pressure. Minimum (ASI_{min}), maximum (ASI_{max}), range (ASI_{range}), and mean (ASI_{mean}) ASI were determined during the gliding phase.

The ski edging angle (in °) was the angle around the ski longitudinal axis. A positive angle indicated an internal ski edging, whereas a negative angle indicated external edging, and an angle equal to 0 reflected a ski laid flat on the snow. Minimum (EDG_{min}), maximum (EDG_{max}), range (EDG_{range}), and mean (EDG_{mean}) ski edging angle were determined during the gliding phase. Ski edging angle and ASI variables were computed for a maximum of steps in the 45-m measurement area, i.e., four to five skiing cycles.

Statistical Analysis

Data are presented as mean and standard deviation (SD). Due to the small sample sizes in each group (six participants), differences between the national- and the regional-level group were examined using Mann–Whitney's *U*-tests for all computed variables. Effect sizes were appraised using Cohen's *d* with threshold values of 0.2, 0.6, 1.2, 2.0, and 4.0 for small, moderate, large, very large, and extremely large effects, respectively (Hopkins et al., 2009). After checking distribution normality with the Shapiro–Wilk test, relationships between T_{glide} and the other computed variables were examined using Pearson's product-moment correlations. Correlation coefficients and 95% confidence intervals (CIs) were computed and used to quantify the correlations magnitudes, with values of 0.1, 0.3, 0.5, 0.7, and 0.9 as thresholds for small, moderate, large, very large, and extremely large, respectively (Hopkins et al., 2009). Correlations between ASI variables and the corresponding ski edging angle variables (e.g., ASI_{min} and EDG_{min}) were also tested. Statistical significance was set at $P < 0.05$.

RESULTS

Skiers in the national-level group showed a 15% longer T_{glide} ($P = 0.04$, $d = 1.71$, large effect), a 32.9 %-point lower ASI_{min} ($P = 0.01$, $d = 2.87$, very large effect), and a 14.6 %-point lower ASI_{mean} ($P = 0.04$, $d = 1.92$, large effect) than their regional level counterparts. There was also a trend to a 27.2 %-point higher ASI_{range} for the national-level skiers ($P = 0.09$, $d = 1.53$, large effect). No between-group differences were found for any of the other studied variables (**Table 2**). These results can be illustrated by the average ASI and ski edging angle signals (**Figures 1A,B**, respectively), for the two groups. ASI increased quasi-linearly from a minimum to a maximum value during the gliding phase for both groups, with a large between-group difference in ASI_{min} at the beginning of the cycle but similar ASI_{max} values at the end of the gliding phase (**Figure 1A**). The ski edging angle also increased all along the gliding phase for both groups, but with a similar pattern (**Figure 1B**).

Table 2 shows the correlation coefficients between T_{glide} and ASI and ski edging angle variables. T_{glide} showed a very large negative correlation with ASI_{min} ($r = -0.79$, 95% CI [−0.94, −0.39], $P < 0.001$, **Figure 2A**) and a very large positive correlation with ASI_{range} ($r = 0.79$, 95% CI [0.41, 0.94], $P < 0.001$, **Figure 2C**). However, T_{glide} was neither correlated to ASI_{max} ($r = 0.32$, 95% CI [−0.31, 0.76], $P = 0.24$, **Figure 2B**) nor correlated to ASI_{mean} ($r = -0.31$, 95% CI [−0.75, 0.32], $P = 0.33$, **Figure 2D**). Only EDG_{range} showed a large positive correlation with T_{glide} ($r = 0.60$, 95% CI [0.04, 0.87], $P = 0.04$), whereas the other ski edging angle variables were not correlated to T_{glide} (**Table 2**).

Finally, ASI_{range} and EDG_{range} showed a large correlation ($r = 0.58$, 95% CI [0.01, 0.87], $P = 0.05$), while no other correlations were found between the other ASI and ski edging angle variables: $r = -0.02$ (CI [−0.59, 0.56]) for ASI_{min} vs. EDG_{min} ($P = 0.95$), $r = -0.27$ (CI [−0.73, 0.36]) for ASI_{max} vs. EDG_{max} ($P = 0.38$), and $r = -0.12$ (CI [−0.65, 0.49]) for ASI_{mean} vs. EDG_{range} ($P = 0.70$).

DISCUSSION

The purposes of this study were to assess the differences in relative glide time and both ski edging angle and plantar pressure mediolateral distribution in skiers of different levels and to further investigate the relationships between these variables. It was hypothesized that the higher-level skiers would demonstrate longer relative gliding phases and more homogeneous plantar pressure distributions in the mediolateral dimension rather than flatter ski edging angles.

First, T_{glide} was significantly greater in skiers of the national- compared to the regional-level group. These results confirm the gliding phase relative duration as a determining factor of ski skating performance (Bilodeau et al., 1992; Stöggl et al., 2008; Losnegard et al., 2017). It should be emphasized that T_{glide} is a computation of *relative* glide time. Interestingly, *absolute* glide time was computed as an additional analysis and was not different between groups (national: 0.61 ± 0.08 s vs. regional: 0.56 ± 0.08 s, $P = 0.38$). This means that the duration of the gliding phase itself is not what differentiates between skiers' level, but rather the ability to lengthen the gliding phase for a given cycle time. This ability could be attributed to both a more effective push-off and/or more effective gliding phase. For that matter, both ASI_{min} and ASI_{mean} were significantly lower, and ASI_{range} tended to be larger in skiers of the national- compared to the regional-level group, which gives some credit to the more effective gliding phase interpretation. **Figure 1A** shows that the national-level skiers began the gliding phase with a plantar pressure more distributed toward the lateral side whereas the regional-level skiers had a plantar pressure already mostly distributed in the medial side. At the end of the gliding phase, the skiers of both groups had approximately the same plantar pressure distribution, with most of the pressure on the medial area that is needed to optimize the following push-off (Smith, 2000). The national level skiers seem to be able to position their center of mass more laterally relatively to the ski than the lower-level skiers in preparation to the gliding phase. This may allow them to put their body mass

TABLE 2 | Mean ± SD values of the studied variables for the two groups and correlation coefficients (*r*) with the relative glide time.

Variables	Mean ± SD		Group effect	Effect size	Correlations to $T_{glideREL}$		
	National	Regional	*P*	Cohen's *d*	*r*	*r* 95% CI	*P*
T_{glide} (%)	51.8 ± 3.6	43.9 ± 6.2	**0.04**	1.71 large	–	–	–
ASI_{min} (%)	−19.8 ± 10.8	11.6 ± 13.1	**0.01**	2.87 very large	−0.79	[−0.94, -0.39]	**<0.001**
ASI_{max} (%)	74.5 ± 13.8	77.0 ± 15.8	0.82	0.18 trivial	0.32	[−0.31, 0.76]	0.24
ASI_{range} (%)	94.3 ± 20.2	67.1 ± 18.7	0.09	1.53 large	0.79	[0.41, 0.94]	**<0.001**
ASI_{mean} (%)	28.8 ± 2.5	43.4 ± 11.5	**0.04**	1.92 large	−0.31	[−0.75, 0.32]	0.33
EDG_{min} (°)	−6.6 ± 1.8	−7.7 ± 3.3	0.75	0.45 small	0.05	[-0.54, 0.61]	0.88
EDG_{max} (°)	8.9 ± 2.9	6.5 ± 2.8	0.17	0.92 moderate	0.42	[−0.21, 0.80]	0.17
EDG_{range} (°)	15.5 ± 1.6	14.2 ± 2.0	0.34	0.79 moderate	0.60	[0.04, 0.87]	**0.04**
EDG_{mean} (°)	0.3 ± 2.2	−1.6 ± 2.5	0.26	0.88 moderate	0.39	[−0.23, 0.79]	0.21

Bold P-values indicate statistical significance.

ASI/EDG_{min}, minimum of the asymmetry index/ski edging angle at the beginning of the gliding phase; ASI/EDG_{max}, maximum of the asymmetry index/ski edging angle at the end of the gliding phase; ASI/EDG_{range}, range of the asymmetry index/ski edging angle during the gliding phase; ASI/EDG_{mean}, mean of the asymmetry index/ski edging angle during the gliding phase.

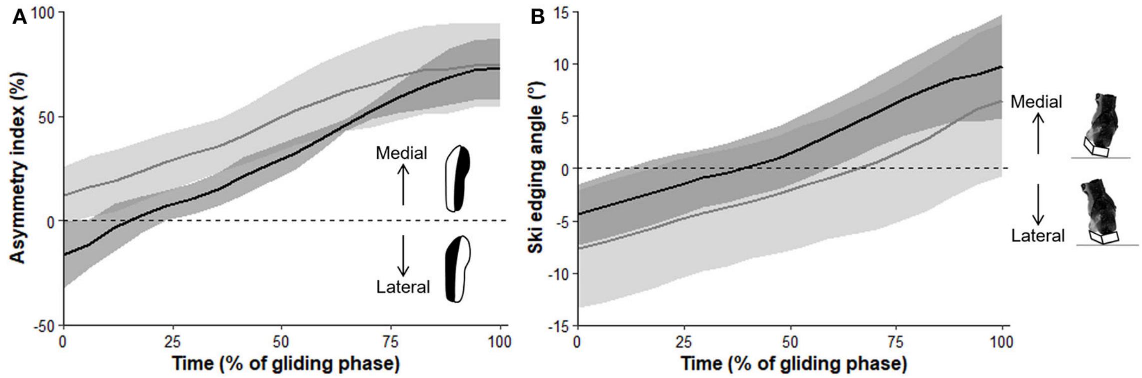

FIGURE 1 | Time courses of the asymmetry index **(A)** and ski edging angle **(B)** during the gliding phase. Data are mean (thick solid lines) ± SD (shaded area) for the national-level group (black) and the regional-level group (gray).

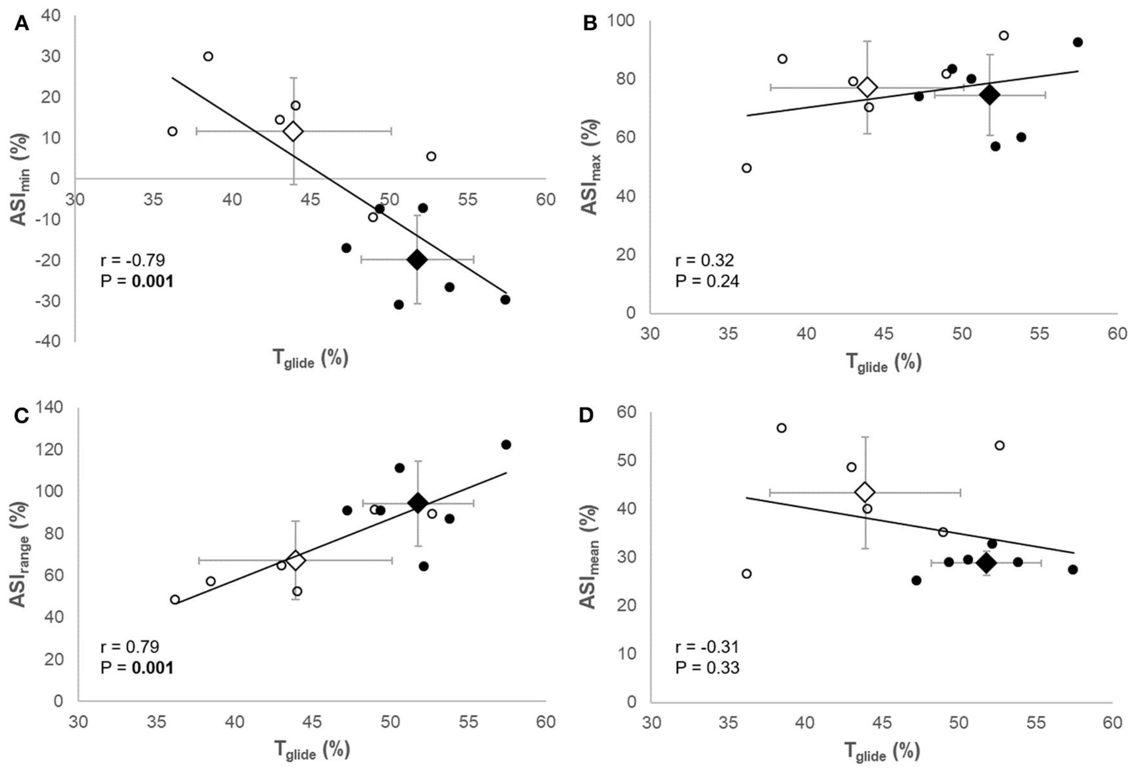

FIGURE 2 | Correlations between the relative glide time (T_{glide}) and minimum value [ASI_{min} **(A)**], maximum value [ASI_{max} **(B)**], range [ASI_{range} **(C)**], and mean value [ASI_{mean} **(D)**] of the asymmetry index during the gliding phase. Circles represent individual datapoints and diamonds represent the mean ± SD of the group (open: regional level, solid: national level).

more directly above the ski (Smith and Heagy, 1994; Stöggl and Holmberg, 2015), potentially giving them more stability (with less muscle isometric contraction) to be able to lengthen the gliding phase. Further research including propulsion forces analysis is needed to understand whether the longer gliding phases demonstrated by the higher-level skiers can also be attributed to more effective push-off. Oppositely, no differences were observed between the national and regional level skiers for any of the ski edging angle variables (**Figure 1B**). Thus, ski edging angle may be of lesser importance in discriminating the skiers' level of performance.

Moreover, T_{glide} was positively correlated to ASI_{min} and ASI_{range} (**Figures 2A,C**, respectively), which supports the association between differences in T_{glide} and differences in ASI variables observed between groups. These results indicate that skiers with the longest gliding phases had a greater ASI variation during gliding because of a lower value at the beginning of the step, i.e., more pressure on the foot lateral area. No correlation existed between T_{glide} and ASI_{max} (**Figure 2B**), indicating that the pressure distribution at the end of the gliding phase did not influence the gliding phase duration. As previously mentioned, this evolution of the plantar pressure distribution from the lateral to the medial area might be associated with a mass transfer above the ski during the gliding phase. This interpretation is in line with the results of a recent study showing that the majority of the V2 kinematics variance was occurring in the mediolateral dimension, and especially for the center of mass kinematics (Gløersen et al., 2018). Indeed, forces (and consequently pressure) applied to the foot are important to maintain stability on the ski, particularly during the gliding phase. The plantar pressure distribution can thus inform indirectly on the position of the skier's center of mass above the ski. The present results suggest that longer gliding phases were allowed by the ability to position the center of mass directly above the ski (and even laterally) at the beginning of the gliding phase, as also proposed by Stöggl and Holmberg (2015). These results are also in line with those of Losnegard et al. (2017) who observed that longer glide times were associated with a greater center of mass mediolateral movement amplitude during the skiing cycle. Further research is needed to confirm the relationships between relative glide time, plantar pressure mediolateral distribution, and center of mass mediolateral movements using motion capture measurements.

We also hypothesized that a flat ski edging angle during the gliding phase would not necessarily be associated to relative glide time. This second hypothesis was partially confirmed since a significant correlation was found between T_{glide} and EDG_{range}. However, neither EDG_{range} nor any other ski edging angle variable was different between the skiers of national and regional level. Thus, it can be argued that ski edging angle variables could be of less importance in quantify skiers' technical ability. Indeed, all skiers did have ski edging angle variations during the gliding phase, consistently with the observations of Smith and Heagy (1994). The present results also showed that neither ski edging angle at ski–snow contact (EDG_{min}) nor average ski edging angle during the gliding phase (EDG_{mean}) was related to relative glide time or performance. Thus, the widespread practical recommendation from coaches to athletes of keeping the ski flat on the snow might not be relevant.

However, even if there was no period with $\sim 0°$ edging angle during the gliding phase for any skier, the minimum and maximum ski edging angles were only $\pm$ 7–8° from flat on average (**Table 2**). It seems that all participants were able to hold this modest amount of edging, which may have had little effect on ski glide (Smith, 2000). One limitation is that ski edging angle was measured in a global reference frame (i.e., earth based); thus, absolute values could have been slightly biased by the snow track inclination. As the track inclination in the present study was only 2.5°, the maximal potential bias was assumed to be very low and not to challenge the present findings.

It is worth mentioning that apart from a correlation between ASI and ski edging angle range, none of the other ASI and ski edging angle variables were correlated to each other. This shows that plantar pressure distribution and ski edging angle bring different information about a skier's technique. This result might seem a little surprising as rotation of the ski along its longitudinal axis (i.e., edging) can be initiated by shifting the skier's mass on one edge or the other. However, small movements in the frontal plane may have occurred at the ankle, thus impacting edging angle but not plantar pressure distribution. This is supported by previous studies on postural control on inclined surfaces, which showed low shift of center of pressure position when standing on an inclined surface (Kluzik et al., 2005; Lin and Nussbaum, 2012). This confirms that longer gliding phases in the present study may have been achieved by a better mediolateral mass transfer above the ski while keeping a moderate edging angle.

One limitation of the present study is that only specific factors (i.e., ski edging and plantar pressure distribution) influencing glide time were studied. Further research is needed to get a more extensive understanding of which factors influence ski edging and plantar pressure distribution during the gliding phase in V2 skating. Since upper body strength was previously demonstrated as a strong predictor of V2 skating performance (Stöggl et al., 2011), pole forces might be interesting to measure to know whether they affect glide time directly through higher propulsive power or indirectly through improving mediolateral balance and in turn plantar pressure distribution during gliding phase. Another limitation concerns the relatively low speed used in this study ($4.2\,m\ s^{-1}$). This speed was chosen to be a representative slow training pace, and this was confirmed by the participants' feedback. This allowed the skiers of both groups to ski at a low physiological intensity and produce relatively moderate forces, so that the results were assumed not to be due to differences in physiological of force production capacities between the skiers. In other words, this slow speed permitted to rule out a potential bias, and the present results can be quite certainly attributed to different technical abilities between the skiers. A follow-up of this research should include higher speeds and test the influence of skiing velocity on the ski edging and plantar pressure distribution variables. Given the results obtained presently at low speed, it can be reasonably assumed that similar observations would be made at higher velocities. Finally, the concurrent use of group comparisons and correlation analyses is delicate as the groups may directly be responsible for the correlations if they form two distinct clusters. The present results suggest it was not the case here since the data points rather scatters as a continuum, including within the groups (**Figure 2**). Yet, given the low number of participants, further research is mandatory more participants of homogeneous level to further support the relationships observed between relative glide time and ASI variables.

The present results may have implications for V2 technique teaching to young cross-country skiers. They support that for a given speed, an increased relative gliding time is related to performance, giving the skier a longer recovery between two push-offs. While a traditional advice from coaches and instructors is to focus on keeping the ski flat to enhance gliding, the present results also imply that the skiers must try to put a substantial part of their mass on the lateral foot area at the beginning of the step, in order to have a large transfer to the medial area during the gliding phase. Further research is needed to assess the relationship between gliding time and push-off effectiveness, in order to complement the aforementioned implications for coaching. Future work should also study the variables measured in the present study at higher speeds and in different ski skating techniques.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the local institutional ethics committee of the Savoie Mont-Blanc University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SP set up and conducted the experiment, processed the data, and wrote the manuscript. FH participated in the experiment setup and reviewed the manuscript. GM participated in the interpretation of the results and reviewed the manuscript. NH reviewed the manuscript. PS set up the experiment, participated in the interpretation of the results, and reviewed the manuscript. All authors contributed to the article and approved the submitted version.

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Talent Development in Young Cross-Country Skiers: Longitudinal Analysis of Anthropometric and Physiological Characteristics

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Introduction: Very little is known about talent development and selection processes in young cross-country skiers.

Aim: (1) to analyze the effect of age on anthropometric and physiological parameters in medium-to-high level cross-country skiers during the late teenage period; (2) to describe parameters' trend in selected talents after the late teenage period; (3) to define which characteristics during the late teenage period could discriminate against further talent selection.

Method: We found 14 male (M) and nine (F) athletes in our database, identified as talents by regional teams during the late teenage period, who performed the same diagonal-stride roller-skiing incremental test to exhaustion at 17 and 18 years old. Of these, four M and three F teenagers performed four further evaluations, and were selected by the national team. Age effect during the late teenage period was verified on anthropometric and physiological parameters measured at maximal intensity (MAX), first (VT1), and second (VT2) ventilatory thresholds, and 3° and 6° of treadmill incline. An observational analysis allowed to evaluate parameters' trend after the late teenage period in selected athletes, and to determine possible characteristics early discriminating further selection.

Results: During the late teenage period, height, weight, and BMI was still raising in M as well as $V'O_2$ at VT2 and 6° of treadmill incline (all $P > 0.05$). In F, mass-scaled $V'O_2$ MAX increased while heart rate (HR) at MAX and VT2 decreased (all $P > 0.05$). Since the late teenage period, all selected males showed maximal ventilation volumes, absolute $V'O_2$ at MAX, VT1, and VT2 that were within or above the 75th percentile of their group; the same was found in selected females for mass-scaled $V'O_2$ MAX, VT1, and VT2 time. After the late teenage period, all selected athletes showed an increasing trend for VT2 time, while a decreasing trend for sub-maximal energetic cost, $\%V'O_2$ and HR.

Discussion: During the late teenage period, males are still completing their maturation process. Since the late teenage period, some physiological parameters seem good indicators to early discriminate for further talents. A progressive increase in skiing efficiency was demonstrated in developing talents of both sexes after the late teenage period.

Keywords: adolescence, performance, physiological indicators, talent selection, age

INTRODUCTION

Cross-country (XC) skiing has received much attention in last few decades and the number of investigations addressing the many aspects related to this sport discipline has grown incredibly. Scientific literature provides a rich and updated panorama about the physiological characteristics of adult skiers from high to top performance levels, as well as the determinants of performance in this sport (Eisenman et al., 1989; Hoffman and Clifford, 1992; Holmberg, 2015; Hebert-Losier et al., 2017; Sandbakk and Holmberg, 2017; Losnegard, 2019; Zoppirolli et al., 2020). It emerged that best adult XC skiers present exceptionally high sport-specific maximal oxygen consumption ($V'O_2$ MAX) values (between 80 and 90 and between 70 and 80 mL·min·kg^{-1}· min^{-1} for men and women, respectively) ventilation volumes (higher than 230 L·min^{-1}), anaerobic capacity, upper-body strength, and power (Eisenman et al., 1989; Hoffman and Clifford, 1992; Hebert-Losier et al., 2017; Sandbakk and Holmberg, 2017; Losnegard, 2019) as well as skiing efficiency (Sandbakk et al., 2010a,b).

On the other hand, less is known about the physiological characteristics of young XC skiers aged between 17 and 20 years. It was demonstrated that the physiological intensity sustained during XC skiing races lasting < 25 min equals the onset of blood lactate accumulation (OBLA) intensity (considered as 4 mMol·L^{-1} of blood lactate concentration) in junior female skiers aged between 17 and 19 years (Welde et al., 2003). It is also known that around 18 years old, sprint (Sandbakk et al., 2011) to mid-distance (Larsson et al., 2002) XC skiing performance is related to absolute running $V'O_2$ MAX, as well as to the absolute oxygen consumption at ventilatory thresholds and OBLA intensities (Larsson et al., 2002) in male athletes, while it is related to physiological parameters at unitary respiratory quotient in females (Larsson et al., 2002). Raising the subjects' OBLA by emphasizing the volume of polarized training has been suggested to be of particular importance for these athletes (Welde et al., 2003; Sandbakk et al., 2011). Additionally, roller-skiing time trials using double-poling, diagonal-stride, or running (around 6, 10, and 10 min, respectively) are accurate predictors of both sprint and distance skiing performance (the two rankings being strongly correlated), for both male and female junior XC skiers of 18 years of age (Carlsson et al., 2014).

Even less is known on younger athletes, although they are encouraged to train intensely from an early age. For XC skiing it was suggested that during puberty, maturity offset (*i.e.,* time distance from peak height velocity at the moment of the athlete' performance evaluation) is an important confounding factor that influences the majority of the existing relationships between XC skiing performance and physical skills (Stöggl et al., 2015, 2017). For instance, it was shown that the correlations between XC skiing performance and the various physical skills in male athletes are reduced or even annulled when maturity offset is entered as a covariate in the data analysis (Stöggl et al., 2015, 2017).

Very little has been published about the longitudinal evolution of physiological parameters in young XC skiers, as well as about the talent recognition process, from detection to selection (Williams and Reilly, 2000). To the best of our knowledge, only two early longitudinal studies reported the development of $V'O_2$ MAX and anaerobic threshold during adolescence in well-trained athletes (Rusko, 1987, 1992). It was shown that $V'O_2$ MAX increases from pre-puberty to adolescence with a trend to level-off after 20 years of age, and with international level XC skiers being able to further improve even after the teenage period. Moreover, the percentage of $V'O_2$ MAX measured at anaerobic threshold tended to be constant over time in those athletes (Rusko, 1987, 1992). On the other hand, in the current literature, anthropometric or physiological parameters of young XC skiers that can possibly predict further success in XC competitions have not yet been identified.

Concerned the process of talent identification/selection in sport activities, it was suggested that an evaluation of the "current status" of athletes might increase the risk of false positives or negatives (Pickering and Kiely, 2017), because of the influence of maturation state, individual trainability, and residual trainability after the teenage period. This approach was suggested to promote the selection of high-performing individuals at the present time, rather than identifying those individuals with the greatest capacity to improve. An "*a posteriori*" approach, based on the comparison of data from different groups of young athletes that subsequently had further success, seemed to be a valid alternative strategy in the process of talent identification or selection (Pickering and Kiely, 2017), that might also include XC skiing.

Thus, the aims of our investigation were (i) to analyze the effect of age on anthropometric and physiological characteristics measured during the late teenage period (well over the occurrence of peak maturation velocity) in XC skiers already identified by regional teams, (ii) to describe the trend of the measured parameters in selected talents after the late teenage period, in the athletes selected by the national team; (iii) to observe "*a posteriori*" which characteristics during the late teenage period might help with further talent selection, by discriminating who was subsequently selected by the national team from who was not. According to previous investigations, we hypothesized the effect of age on the anthropometric characteristics of male athletes during the late teenage period as well as a potential role of maximal

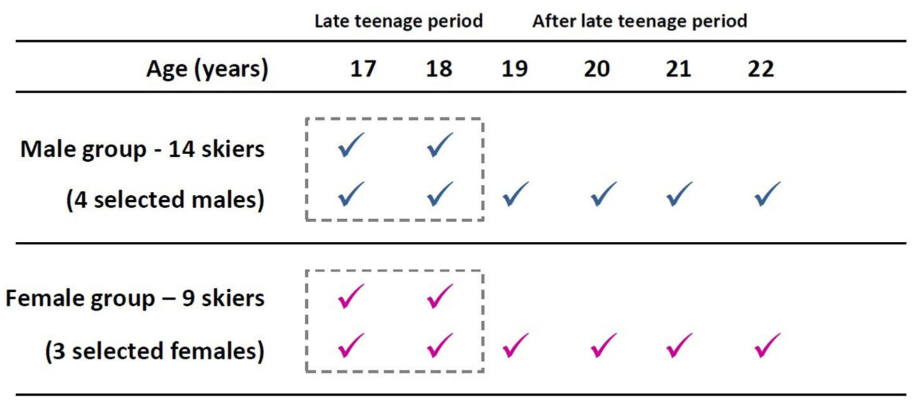

FIGURE 1 | Visual overview of the longitudinal research. The figure shows the time-course of the tests yearly performed by male (blue) and female (purple) athletes. All the athletes performed two consecutive evaluations from 17 to 18 years of age, while only the selected athletes did six consecutive evaluations from 17 to 22 years of age. Late teenage (dotted-lined boxes) and after late teenage periods were here represented.

oxygen consumption, ventilation, and occurrence of ventilatory thresholds in discriminating talented XC skiers since their late teenage period. Moreover, we hypothesized that also skiing economy, as a measure of the technical skills, would discriminate future performance levels in adolescent XC skiers.

METHODS

The study design was planned as a longitudinal and observational research.

Inclusion Criteria for Data Analysis

We searched our database for Italian male (M) and female (F) XC skiers that (i) had come into our laboratories for testing purposes since the age of 17, as members of XC skiing regional teams or Italian national team, (ii) had performed the same diagonal-stride roller-skiing protocol for the evaluation of maximal physiological parameters and ventilatory thresholds (iii) had skied on the same treadmill and with the same roller-skiing technique, (iv) had skied for consecutive years [at least 2 for skiers identified by the regional teams only, at least 6 for the skiers further selected by the National team (**Figure 1**)], (v) had been tested between October and November (to monitor the same period of training periodization) from 2008 to 2019.

Testing Protocol, Instruments, and Materials

All the skiers observed at least 48 h of low-intensity training before testing, free hydration was allowed. Before testing, athletes' weight and height were measured in underwear by a digital scale with a resolution of 0.1 kg, and barefooted through a stadiometer with 0.001 m resolution, respectively. Roller-skiing testing procedures were performed in the same laboratory, with temperature and humidity being kept constant during the test sessions (i.e., 18°C and 60% rH, respectively).

The roller skies testing protocol (designed in agreement with coaches since 2007) consisted of (i) 10 min warm-up with the diagonal-stride technique at 2° of treadmill slope and 10 or 9 km·h^{-1}, for M and F, respectively—this procedure induced a similar warm-up of roller-skis' wheels, thus reducing rolling friction coefficient differences among skiers; (ii) 10 min rest during which athletes were equipped with heart rate monitor and mask for metabolic measurements; (iii) an incremental test performed consistently with the diagonal-stride technique, starting from the mechanical intensity of the warm-up and increasing the treadmill slope by 1° every 3 min, until voluntary exhaustion.

All the tests analyzed in the present investigation were performed on the same 2.5 × 3.5-m motor-driven treadmill (Rodby Innovation AB, Vänge, Sweden). The athletes always used their own ski boots, while poles and roller-skies were provided by the lab. The poles (ONE WAY Sport Oy, Helsinki, Finland) were equipped with special tips designed not to slip on the treadmill belt surface during arm poling and were available at multiple lengths with 2.5 cm differences. The athletes were asked to use their usual pole length taken during classic competitions. The roller-skies used across several years of testing (Ski Skett Nord CL, Crestani Sport, Sandrigo, Italy) were the same as far as concerns the metallic structure, while the wheels were regularly changed for new wheels of identical characteristics every 100 h of usage, due to rubber consumption. However, friction coefficient measured after each wheel change (Pellegrini et al., 2011) ranged from 0.0230 to 0.0237, ensuring a constant friction coefficient across the different testing sessions.

During the maximal incremental test to exhaustion, ventilatory parameters were continuously collected by a breath-by-breath metabolic cart. Across the several years of testing, two metabolic carts of the same company have followed each other, due to the renewal of the laboratory equipment (Quark b2, Cosmed, Rome, Italy and C-PET, Cosmed, Rome, Italy). In both cases, the athletes wore an appropriately sized facial mask (70 mL dead space) to direct the respiratory flows coming from mouth and nose to the air gas analyzers, through a sampling tube. Ventilatory volumes were measured by the optic reading of the movement velocity of a low-resistance bidirectional turbine incorporated in the mask. Before each test, the gas analyzers and the turbine were calibrated according to manufacturing guidelines with ambient air (20.93% for oxygen and 0.03% for carbon dioxide), a gas tank with a known concentration of gasses (16.00 ± 0.04% oxygen and 5.00 ± 0.01% carbon dioxide) (Air Liquide Italia S.p.A., Milan, Italy), and a 3-L volume syringe.

At the end of each 3-min stage, the skiers stopped poling with the left upper-limb so that a sample of peripheral blood could be taken from the fingertip and collected in a 25-μL capillary tube. A sample of blood was also taken at the end of the test. Blood lactate concentration was measured using a digital blood lactate analyzer (Biosen C-line, EKF Diagnostic, GmbH, Magdeburg, Germany). Heart rate was measured continuously during the test with a wireless monitoring system (Polar Electro Oy, Kempele, Finland) connected to the metabolic cart.

First (VT1) and second (VT2) ventilatory thresholds were detected by visual inspection of two independent researchers familiar with testing reporting. VT1, considered as an indicator of lactate accumulation, was determined by analyzing a group of different measures including: (i) the first disproportionate increase in ventilation; (ii) an increase in VE/VO_2 with no increase in VE/VCO_2; and iii) an increase in end-tidal O_2 tension with no consequent fall in end-tidal CO_2 tension (Reinhard et al., 1979; Wasserman et al., 1990). VT2, considered as an indicator of metabolic acidosis development, was determined by detecting (i) the second disproportionate increase in minute ventilation; (ii) the first systematic increase in VE/VCO_2; and (iii) the first systematic decrease in end-tidal CO_2 tension (Reinhard et al., 1979; Wasserman et al., 1990). Maximal physiological parameters were defined as the highest value after 20-s of data smoothing (Robergs et al., 2010), while maximal lactate concentration was measured at the end of the test. The physiological values relative to each test stage were considered as the average values of the last 30 s of each stage, after 5-s of data smoothing (Sandbakk et al., 2010a; Zoppirolli et al., 2015).

Parameters Analyzed

Weight, height, and BMI were analyzed as anthropometric parameters. Maximal absolute and mass-scaled oxygen consumption ($V'O_2$ MAX and $V'O_2$ MAX $\cdot kg^{-1}$, respectively), ventilation (V' MAX), heart rate (HR MAX), maximal blood lactate concentration (Blood Lactate MAX), and time to exhaustion (Time MAX) were considered as maximal values. Moreover, absolute and percentage oxygen consumption at VT1 and VT2 ($V'O_2$ VT1, %$V'O_2$ VT1, $V'O_2$ VT2, %$V'O_2$ VT2), absolute and percentage heart rate (HR VT1, %HR VT1, HR VT2, %HR VT2), and blood lactate concentration (Lactate VT1, Lactate VT2) were examined to compare athletes at the same physiological relative intensities. The time at which the first and second ventilatory thresholds occurred (Time VT1, Time VT2) was also considered. Finally, to compare athletes at the same absolute mechanical intensity, absolute and relative oxygen consumption was measured at 3° and 6° of treadmill incline ($V'O_2$ 3°, %$V'O_2$ 3°, $V'O_2$ 6°, %$V'O_2$ 6°), absolute and relative heart rate (HR3°, %HR3°, HR6°, %HR6°), blood lactate (Lactate3°, Lactate6°), and energetic cost (EC3°, EC6°) were examined. Energetic cost was estimated by considering both the aerobic and anaerobic contribution to metabolic power, as described previously (Zoppirolli et al., 2015).

Statistical Analyses

Due to the low number of subjects and the high number of parameters analyzed, a non-parametric statistical analysis was used. In the text, data are presented as median and 95% confidence intervals (*CI*). In the figures (from **Figures 2–7**), the box plot shows medians of male (-M) and female (-F) groups, with 10, 25, 75, and 90th percentile during the late teenage period. A *Wilcoxon Signed-Rank Test* for paired samples was applied to analyze the effect of age during the late teenage period (between 17 and 18 years old), for both sexes independently. Statistical analysis was carried out using statistical software (SPSS 11.0, SPSS Inc., Chicago, IL, USA) and statistical significance was set at $P < 0.05$.

Moreover, a descriptive analysis was used to evaluate the trend of measured parameters after the late teenage period in M and F selected athletes, independently, as well as to identify possible parameters associated with further selection since the late teenage period in the two sexes. After the late teenage period, a likely increasing or decreasing trend was considered if all the selected athletes showed at least three consecutive increasing or decreasing values from the age of 18 onward, and if all the values measured at the age of 22 were above or below the 75 or 25 percentile, respectively, than the values measured at the age of 18. During the late teenage period, the parameters in the selected athletes that showed values within/above the 75th percentile, or within/below the 25th percentile at both 17 and 18 years of age, were considered as possible characteristics predicting further athlete selection.

RESULTS

Fourteen M and nine F XC skiers meeting all the inclusion criteria required for the analysis were found. After the late teenage period, four M and three F continued to be evaluated as they were selected for the national team (**Figure 1**). **Figure 2** shows anthropometric characteristics while **Figure 3** displays maximal physiological values as well as time to exhaustion data over progressive chronological age, both for males (M) and females (F). **Figures 4**, **5** show physiological values at VT1 and VT2, respectively, as well as time to reached thresholds in males (M) and females (F). **Figures 6**, **7** show physiological values at 3° and 6° of treadmill incline, respectively, as well as EC of diagonal skiing at 10 and 9 $km \cdot h^{-1}$ for males (M) and females (F), respectively. In the figures, statistical results for age effect during the late teenage period was indicated.

Anthropometry and Physiological Values During the Late Teenage Period

Height, weight, and BMI was still raised between 17 and 18 years old in M athletes ($P = 0.016$, $= 0.001$, and 0.013, respectively),

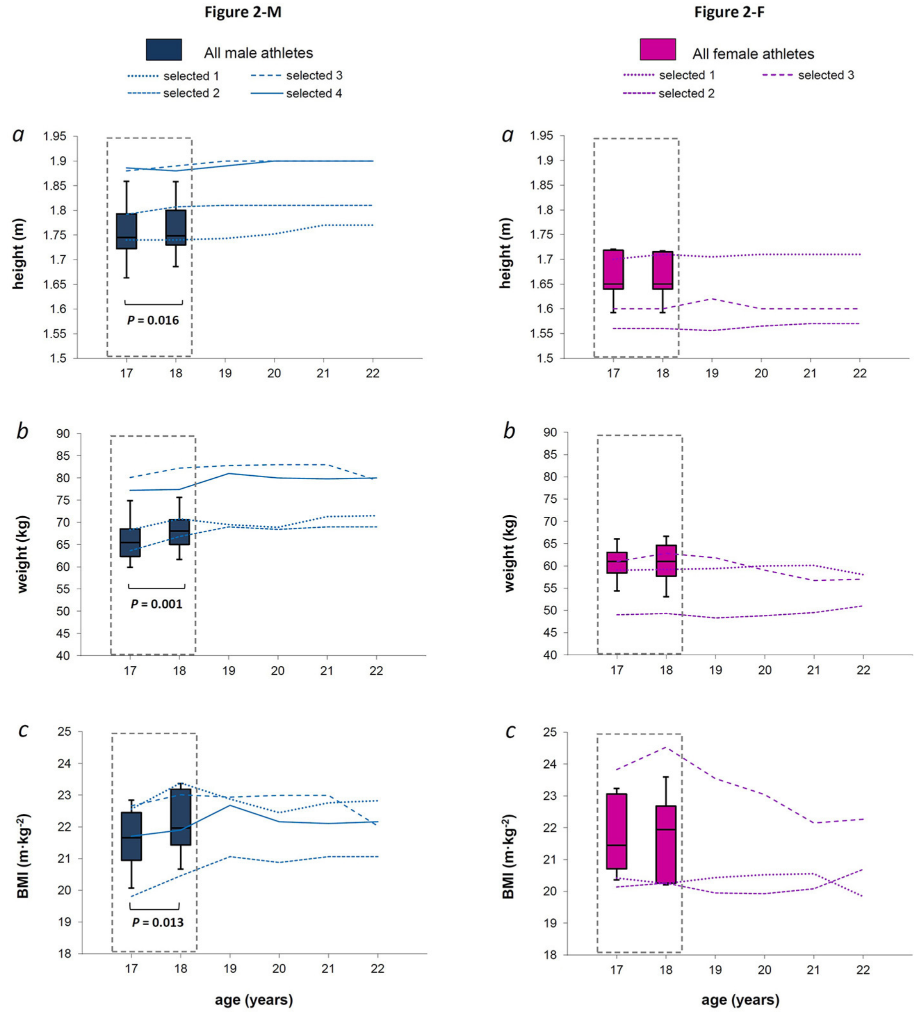

FIGURE 2 | Figures 2-M and 2-F. For males and females (Figures 2-M and 2-F, respectively), the box plot represents medians, 9, 25, 75, and 90th percentiles of height, weight, and BMI (panel *a*, *b,* and *c*, respectively), measured over the late teenage period (data in dotted-lined boxes) in the entire group. The *P*-value refers to the statistical age effect during the late teenage period. In each panel, the line plots represent each selected athlete from 18 to 22 years of age.

with a median difference of 0.01 m (95% *CI* 0.01), 1.7 kg (*CI* 0.7), and 0.46 kg·m^{-2} (*CI* 0.27), respectively. However, these anthropometric parameters did not change in females [all $P >$ 0.05, median difference of 0.00 m (*CI* 0.00), 0.3 kg (*CI* 0.8), and 0.12 kg·m^{-2} (*CI* 0.32), respectively] and did not appear to be linked to further success in both sexes (**Figures 2-M** and **2-F**; panel *a*, *b,* and *c*, respectively). Concerning maximal values, we did not find any effect of age in the M group (all $P >$ 0.05, **Figure 3-M**). In the F group (**Figure 3-F**), V'O_2 MAX·kg^{-1} (**Figure 3-F** panel *b*) was found to increase with age [$P =$ 0.050, median difference of 3.3 mL·min^{-1}·kg^{-1} (*CI* 2.8), while HR MAX (**Figure 3-F** panel *d*) decreased ($P = 0.011$, median difference of −1 bpm (*CI* 1.2)] between 17 and 18 years of age. All selected M athletes showed V'O_2 MAX (**Figure 3-M** panel *a*) and V'MAX (**Figure 3-M** panel *c*) values that were within or above the 75th percentile of the entire male group, at both 17 and 18 years of age, with the selected showing a median value of 4.9 L·min^{-1} (with 0.2 L·min^{-1} *CI*) for V'O_2 MAX and 198 L·min^{-1} (*CI* 14) for V' MAX, between 17 and 18 years of age. All F selected athletes showed V'O_2 MAX·kg^{-1} values (**Figure 3-F** panel *b*) that were within or above the 75th percentile of the entire female group, at both 17 and 18 years of age, with the selected showing a median value of 59.0 mL·min^{-1}·kg^{-1} (*CI* 3.6) in that age period.

When considering comparable relative physiological workloads (intensities associated to VT1 and VT2), only V'O_2 VT2 increased in M athletes between 17 and 18 years of age [**Figure 5-M** panel *a*, $P = 0.050$, median difference of 0.12 L·min^{-1} (*CI* 0.21)], while HR VT2 decreased for both sexes [**Figures 5-M** and **5-F** panel *c*, $P = 0.050$ and $P = 0.011$ for M and F, respectively, with a median difference of −2 bpm (*CI* 1.4) and −3 bpm (*CI* 2.0)]. All selected M athletes showed V'O_2 VT1 and V'O_2 VT2 values (**Figures 4-M** and **5-M**, respectively, panel *a*) within or above the 75th percentile of the entire male group,

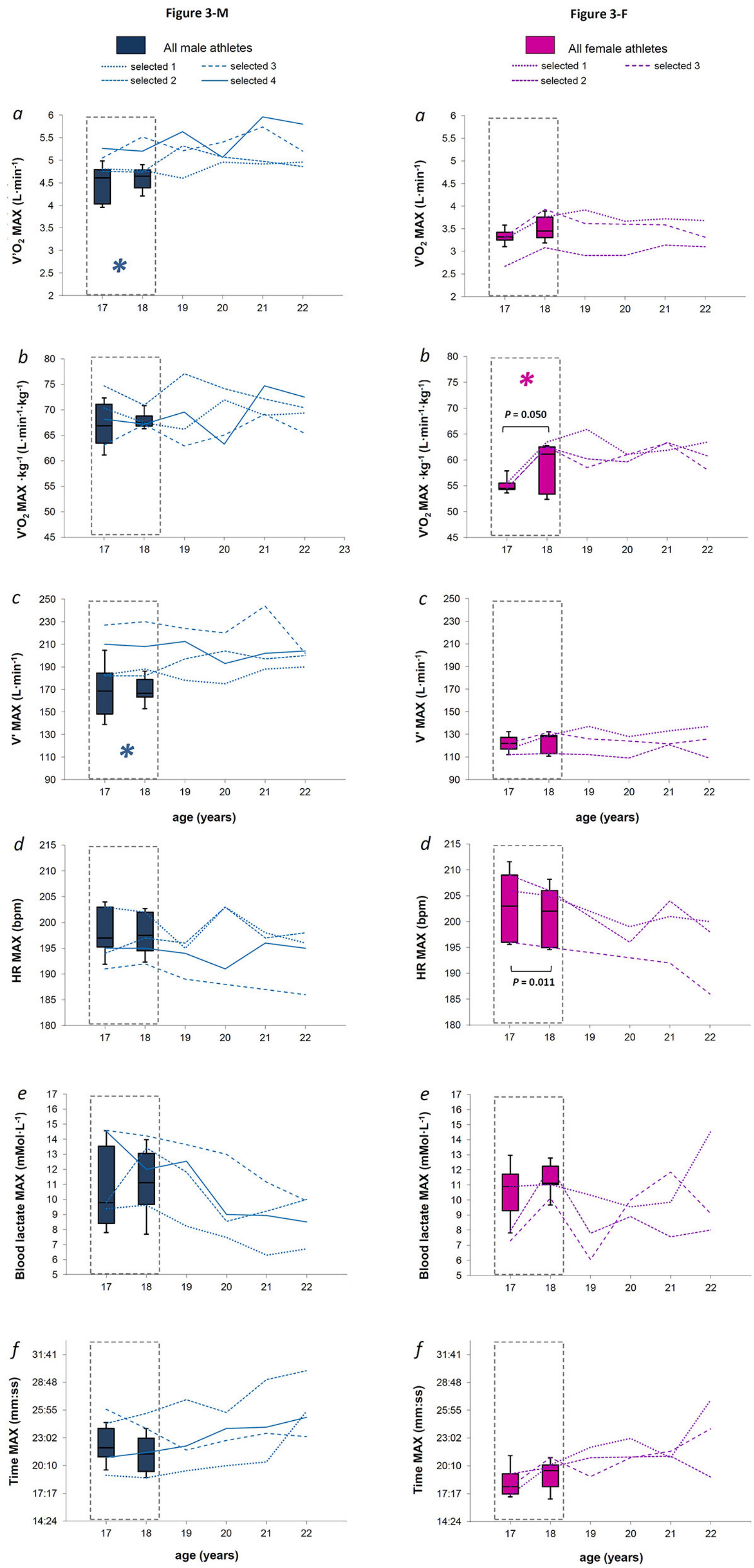

FIGURE 3 | Figures 3-M and 3-F. For males and females (Figures 3-M and 3-F, respectively), the box plot represents medians, 9, 25, 75, and 90th percentiles of maximal values of absolute oxygen consumption (panel *a*), mass-scaled oxygen consumption (panel *b*), ventilation volume (panel *c*), absolute heart rate (panel *d*),

(Continued)

FIGURE 3 | blood lactate concentration (panel *e*), and test time (panel *f*) measured over the late teenage period (data in dotted-lined boxes) in the entire group. The *P*-value refers to the statistical age effect during the late teenage period. In each panel, the line plots represent each selected athlete from 18 to 22 years of age. *****indicates possible parameters early identifying further athletes' selection, when all the criteria presented in the statistical analysis paragraph were satisfied.

at both 17 and 18 years of age, with the selected ones showing a median value of 3.8 L·min^{-1} (*CI* 0.2) for V'O_2 VT1 and 4.3 L·min^{-1} (*CI* 0.2) for V'O_2 VT2. All selected F athletes reached both VT1 and VT2 later than the entire female group, with values of Time VT1 and Time VT2 that were within or above the 75th percentile at both 17 and 18 years of age (**Figures 4-F** and **5-F**, respectively, panel *f*).

When considering specific absolute mechanical intensities (3° and 6° of treadmill incline), only V'O_2 6° tended to increase significantly between 17 and 18 years of age in M skiers [**Figure 7-M**, panel *a*; $P = 0.011$ with a median difference of 0.26 L·min^{-1} (*CI* 0.18)]. In both sexes, any physiological parameters measured at specific absolute mechanical intensities were likely to discriminate against further talent selection (**Figures 7-M** and **7-F**).

Anthropometry and Physiology After the Late Teenage Period in Selected Athletes

Anthropometric parameters as well as physiological values measured at maximal stages apparently did not change after the late teenage period in selected athletes of both sexes (**Figures 3-M, 3-F**, **4-M**, and **4-F**). HR VT1 and %HR VT1 showed a likely decreasing trend in F selected athletes after the late teenage period (**Figure 4-F**, panel *c* and *d*, respectively), while Time VT2 showed a most likely increasing trend in both M and F selected athletes after the late teenage period (**Figures 5-M** and **5-F**, respectively, panel *f*). Many meaningful effects of age apparently occurred in selected athletes of both sexes when analyzing the physiological values elicited by specific absolute mechanical intensities after the late teenage period (**Figures 6-M, 6-F**, **7-M**, and **7-F**). A most likely decreasing trend was observed for EC 3° and EC 6° in both sexes (**Figures 6-M, 6-F, 7-M**, and **7-F**, panel *f)*. In both sexes, a likely decreasing trend in %V'O_2, HR, and % HR at both 3 and 6° of treadmill incline (**Figures 6-M, 6-F**, **7-M**, and **7-F**, panel *b*, *c,* and *d*, respectively) also occurred.

DISCUSSION

Our investigation aimed to longitudinally analyze anthropometric and physiological characteristics in high-level junior XC skiers during the late teenage period, and in selected XC skiers after the late teenage period. Moreover, we aimed to observe *"a posteriori"* which characteristics during the late teenage period could predict further talent selection. The main findings were that anthropometric characteristics were still raised between 17 and 18 years in males, while absolute and relative physiological characteristics at maximal stages, did not change significantly. Absolute V'O_2 at VT2 and moderate sub-maximal intensity increased significantly, while HR at VT2 decreased. In females between 17 and 18 years of age, anthropometric characteristics did not change, while some physiological values at maximal and sub-maximal stages developed significantly (i.e., V'O_2 MAX ·kg^{-1} increased while HR MAX and HR VT2 decreased). Since the late teenage period, the selected males showed high values of absolute (i.e., L·min^{-1}) oxygen consumption and ventilation volumes at maximal stages, as well as high values of absolute oxygen consumption at VTs intensities with respect to the entire group. Since the late teenage period, the selected females showed high values of mass-scaled (i.e., mL·min^{-1}·kg^{-1}) oxygen consumption as well as a later occurrence of VTs with respect to the entire group. Finally, in selected athletes of both sexes a significant decrease in the energetic cost of skiing was observed after the late teenage period at sub-maximal intensities, together with significant reductions in oxygen consumption and heart rate values.

Even though we did not monitor athletes' training habits or race results, we could compare some physiological values measured in male and female athletes at the age of 18 years old in the present investigation with previously published data about Swedish elite XC skiers of the same age (Larsson et al., 2002). Considering maximal physiological values, we found that the male athletes here reached average absolute V'O_2 MAX values of 5.0 ± 0.4 L·min^{-1} (see supplementary material) compared to 5.2 ± 0.6 L·min^{-1} found in the Swedish junior elite, and mass-scaled V'O_2 MAX values of 68.5 ± 2.1 (see supplementary material) compared to 71.1 ± 7.4 mL·min^{-1}·kg^{-1}. The female counterparts showed absolute V'O_2 MAX values of 3.6 ± 0.4 L·min^{-1} (see supplementary material) compared to 3.8 ± 0.2 L·min^{-1} of the Swedish junior elite, and mass-scaled V'O_2 MAX values of 57.3 ± 5.4 (see supplementary material) compared to 59.8 ± 3.2 mL·min^{-1}·kg^{-1}. These data attest that athletes of both sexes identified by the regional teams to compete in the young national XC skiing circuit, and here examined, had on average a high physiological performance capacity, relative to the specific age considered.

Longitudinal Analysis During and After the Late Teenage Period

Anthropometric Parameters

Male skiers showed a significant increase in height, weight, and BMI values between 17 and 18 years [median difference of 0.01 m (*CI* 0.01), 1.7 kg (*CI* 0.7), and 0.46 kg·m^{-2} (*CI* 0.27), respectively], reaching median anthropometric values of 1.74 m (0.04 m *CI*), 68.0 kg (3.2 kg CI,) and 22 kg·m^{-2} (0.36 kg·m^{-2} *CI*) for height, weight, and BMI, respectively (**Figure 2-M**) at 18 years of age. This increasing trend is in line with the still ongoing maturation process in males at that age (Cacciari et al., 2006), confirmed to be valid not only for the general population but also for elite endurance athletes (Steiner et al., 2019). On the other hand, female athletes in our study demonstrated an already completed growth process at 17 years of age, attesting

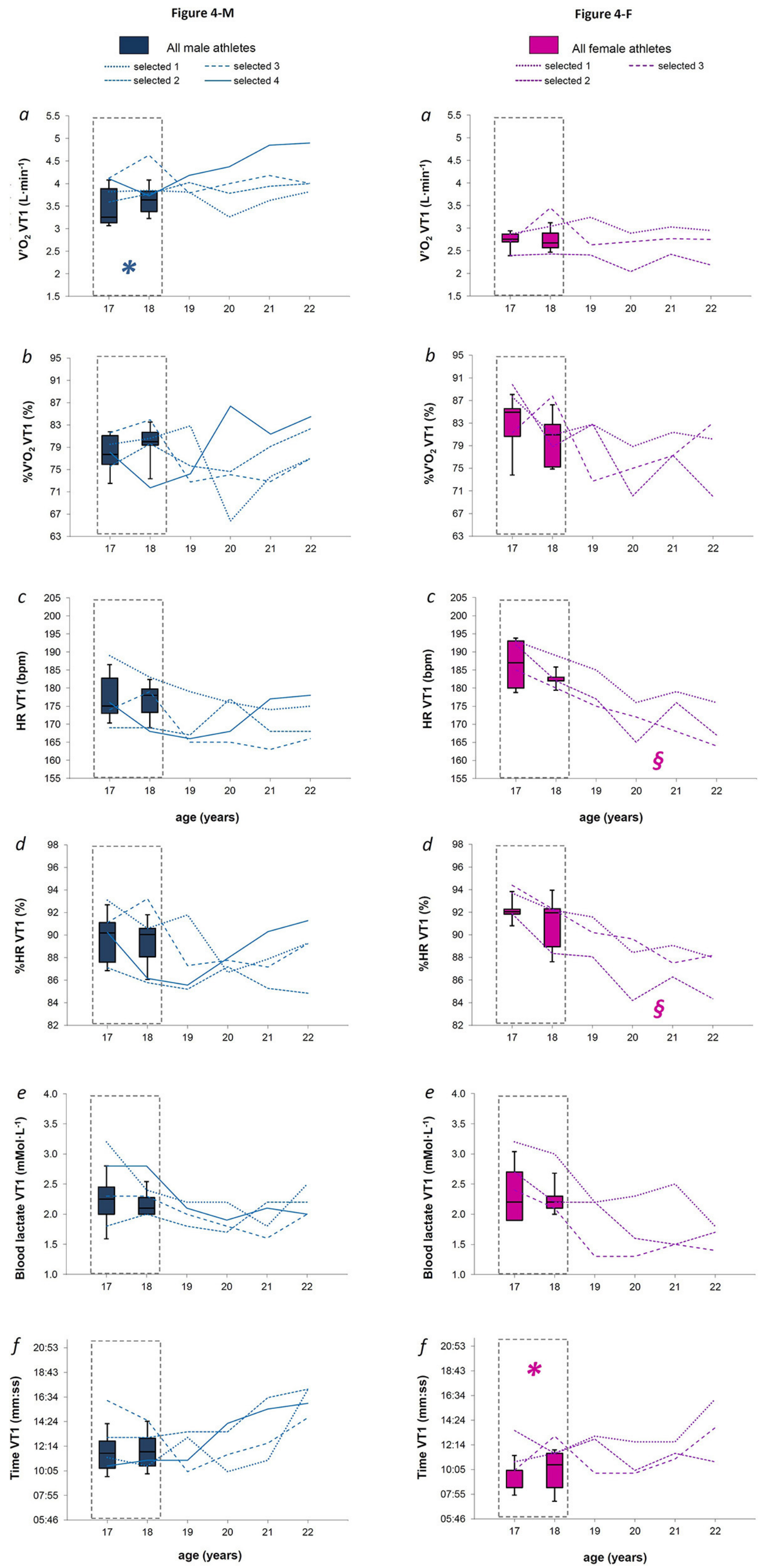

FIGURE 4 | Figures 4-M and 4-F. For males and females (Figures 4-M and 4-F, respectively), the box plot represents medians, 9, 25, 75, and 90th percentiles of the values measured at the first ventilator threshold (VT1) for absolute oxygen consumption (panel *a*), relative oxygen consumption (panel *b*), absolute heart rate

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FIGURE 4 | (panel *c*), relative heart rate (panel *d*), blood lactate concentration (panel *e*), and time of first threshold occurrence (panel *f*) measured over the late teenage period (data in dotted-lined boxes) in the entire group. In each panel, the line plots represent each selected athletes from 18 to 22 years of age. **§** indicates a most likely effect of age after the later teenage period, while ***** indicates possible parameters early identifying further athletes' selection, when all the criteria presented in the statistical analysis paragraph were satisfied.

their median anthropometric values at 1.65 m (0.03 m *CI*), 61.0 kg (3.8 kg *CI*), and 21.7 kg·m^{-2} (0.9 kg·m^{-2} *CI*), for height, weight, and BMI, respectively (**Figure 2-F**). It is well-known that physical maturation process in female adolescents ends earlier than in their male counterparts (Cacciari et al., 2006), due to the anticipated peak growth velocity and development process. Also in males, anthropometric parameters showed a stabilization after the late teenage period, accordingly to general population normative data (Cacciari et al., 2006).

Physiological Parameters at Maximal Exercise Intensity

Absolute and mass-scaled V'O_2 MAX were constant between 17 and 18 years in male skiers (**Figure 3-M**, panel *a*). On the other hand, mass-scaled V'O_2 MAX increased significantly in females in that period (median difference of 6.6 mL·min^{-1}·kg^{-1}) (**Figure 3-F**, panel *b*). Even though a significant increase in V'O_2peak or V'O_2 MAX was observed in both untrained subjects or endurance athletes during pre-puberty and adolescence (Paterson et al., 1987; Naughton et al., 2000; Bjerring et al., 2019; Steiner et al., 2019), it was shown that the rate of V'O_2 MAX is highest around the age of the peak height velocity (12 and 14 years old for females and males, respectively), thus constantly decreasing over years, with V'O_2 MAX values approaching a plateau around the end of the teenage period in both sexes (Geithner et al., 2004). This was also confirmed for adolescent male XC skiers (Rusko, 1987, 1992). On the other hand, the significant increase in mass-scaled V'O_2 MAX here observed in female athletes during the late teenage period is sustained by two previous studies indicating a substantial increase in sport-specific V'O_2peak as a consequence of various training interventions between 16 and 19 years old (Skattebo et al., 2016; Carlsson et al., 2017). Altogether, these data suggest greater adaptations for maximal physiological values in female than in male XC skiers during the late teenage period, presumably due to a different training level at their starting point.

When analyzing the data of the athletes selected by the national team, we found non-appreciable changes in neither absolute nor relative V'O_2 MAX after the late teenage period, in both sexes (**Figures 3-M** and **3-F**, panel *a* and *b*). Even though residual possibilities for a further increase of V'O_2 MAX after 20 years of age have been previously reported for international-level XC skiers (Rusko, 1987, 1992), the low number of selected athletes in our study, together with the type of testing protocol proposed to the athletes (it may not be optimal to measure maximal physiological values because of increments in slope only Midgley et al., 2008) could partially explain the lack of further V'O_2 MAX improvement after the late teenage period in the selected athletes. However, elite adult male XC skiers also reported insignificant changes in V'O_2peak over the preparation and competition phases of one XC skiing season (Losnegard et al., 2013).

We did not find any significant effect of age on maximal blood lactate concentration, maximal ventilation volumes, and time to exhaustion across and after the late teenage period in both sexes (**Figures 3-M** and **3-F**, panel e, c and f respectively). It was previously reported that maximal ventilation increases significantly across age in endurance athletes aged between 10 and 15, as an effect of physical growth (Mercier et al., 1991). As our subjects were near the end of their maturation process, it is reasonable that they had already reached a stable trend for maximal ventilation during the late teenage period.

Physiological Parameters at Sub-Maximal Exercise Intensities

When considering sub-maximal intensities, we found that absolute oxygen consumption at VT2 and moderate sub-maximal exercise intensity increased during the late teenage period in male athletes, in relation to the progressive increase of anthropometric values, while it remained stable in females, as did the anthropometric parameters. Interestingly, a significant decrease of absolute heart rate values was found at the VT2 intensity, maybe as a consequence of endurance training. However, neither blood lactate nor exercise economy changed across the late teenage period in both sexes. Sparse literature describes longitudinal development of physiological parameters related to exercise performance during adolescence (Bragada et al., 2010). When considering previous training studies on junior XC skiers, some investigations showed no changes in skiing economy as a consequence of different training regimes in athletes of this age (Skattebo et al., 2016; Carlsson et al., 2017), while other did (Hoff et al., 1999, 2002).

When analyzing the data of the selected athletes after the late teenage period, it was noted that some parameters changed significantly in both sexes over the years (**Figures 4-M, 4-F**, **5-M, 5-F**, **6-M, 6-F**, **7-M**, and **7-F**). A likely decrease in absolute and relative heart rates was found in male and female athletes at both absolute sub-maximal exercise intensities, and at the VT1 intensity in females, suggesting an increased efficiency of cardiovascular functions after the late teenage period in high-level XC skiers. It was previously reported that endurance training positively influences the growing of both right (D'Ascenzi et al., 2017) and left (Bjerring et al., 2019) heart sides from an early age (10–15 years old) without influencing systolic and diastolic functions at those ages, with respect to sedentary young people (D'Ascenzi et al., 2017; Bjerring et al., 2019). In adolescents (13–19 years old), long-term endurance training (30 min, at least five times a week for at least 2 years) induces both heart structural changes and few functional changes at rest (Rundqvist et al., 2017), revealing that physiological

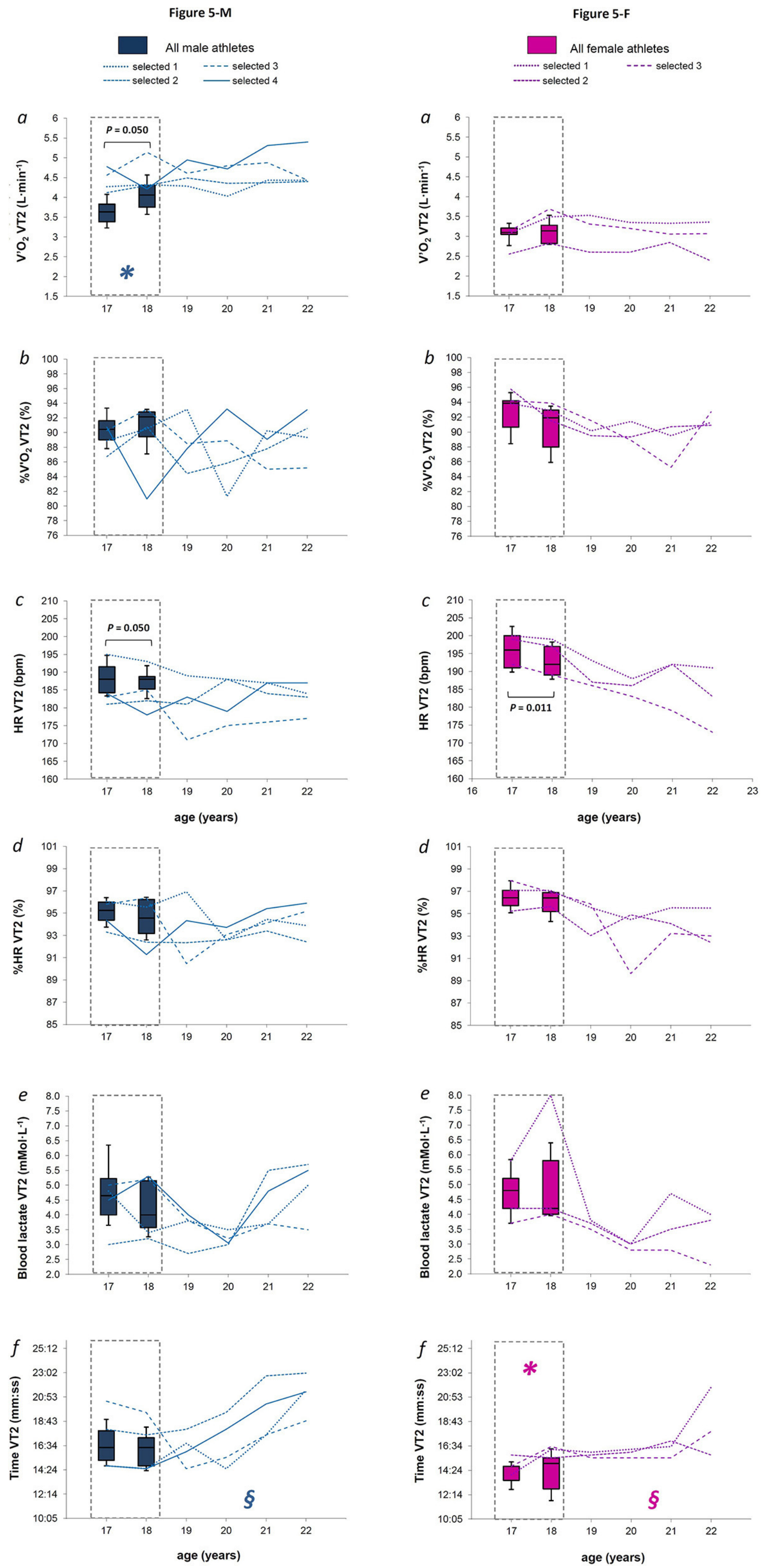

FIGURE 5 | Figures 5-M and 5-F. For males and females (Figures 5-M and 5-F, respectively), the box plot represents medians, 9, 25, 75, and 90th percentiles of the values measured at the second ventilator threshold (VT2) for absolute oxygen consumption (panel *a*), relative oxygen consumption (panel *b*), absolute heart rate

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FIGURE 5 | (panel *c*), relative heart rate (panel *d*), blood lactate concentration (panel *e*), and time of second threshold occurrence (panel *f*) measured over the late teenage period (data in dotted-lined boxes) in the entire group. The *P*-value refers to the statistical age effect during the late teenage period. In each panel, the line plots represent each selected athlete from 18 to 22 years of age. **§** indicates a likely effect of age after the late teenage period, while ***** indicates possible parameters early identifying further athletes' selection, when all the criteria presented in the statistical analysis paragraph were satisfied.

cardiac remodeling occurs due to long-term endurance exercise from early adolescence (Csecs et al., 2020), taking also functional improvements thereafter (Poh et al., 2008).

Also the energetic cost of skiing decreased unequivocally after the late teenage period in selected athletes of both sexes, at both low and moderate exercise intensities. This, together with a decreasing trend for oxygen consumption, indicated a more efficient aerobic energy production at low but also at moderate absolute mechanical intensities. This was in line with a previous study showing how skiing economy improves during the course of preparation and competition phases of a XC skiing season in elite adult athletes (Losnegard et al., 2016), as consequence of physiological and biomechanical improvements due to the great amount of general and specific training. As expected, the time of VT2 occurrence showed a likely increasing trend after the late teenage period in selected athletes, while time for VT1 occurrence did not show an appreciable trend. However, only heart rate at VT1 in females seemed to decrease after the late teenage period, while the rest of the physiological parameters measured at VT1 (oxygen consumption and blood lactate) and VT2 (oxygen consumption, heart rate, and blood lactate) did not show an evident development across years. An early report showed no differences over adolescence for the percentage of V'O_2 MAX measured at anaerobic threshold in well-trained adolescent XC skiers (Rusko, 1987). Some recent investigations confirmed stable physiological values related to VTs in high-level endurance athletes throughout a training season (Lucia et al., 2000; Polat et al., 2018), as already seen for maximal values. Complete physical maturation together with the high level of performance of our athletes since the late teenage period justifies our findings.

Parameters That Characterize Successful Athletes at an Early Stage

Some useful information can be drawn by our data, even though all the stages of talent recognition and nurture are very challenging due to the complex systems surrounding the athletes. Genetics, motivation and attitude to exercise, sport environment, family support, stress resilience, residual trainability, and recovery from injuries all contribute to determine all the phases of this process, from talent detection to talent development (Vaeyens et al., 2009; Issurin, 2017). Sometimes an analysis based on anthropometric and physiological parameters might not be adequate in discriminating during adolescence, athletes that performed successfully at an elite level after the late teenage period, found a predictive prevalence of psychological attributes (Issurin, 2017).

As demonstrated in the previous sections, the athletes monitored here were, on average, of a high level during their late teenage period from a physiological perspective, when compared to the data available in the literature (Larsson et al., 2002). Thus, we have analyzed talents already identified in early stages of their sport career, and developed under the guidance of the regional teams. Unfortunately, to our knowledge no literature is available about talent identification or selection in young XC skiers, and finding an interpretation supporting our data is challenging. However, we can compare "*a posteriori*" the characteristics of selected athletes with the data of the entire group during the late teenage period, trying to identify possible anthropometric or physiological parameters that characterize elite XC skiers at an early stage.

In both sexes, anthropometric parameters seemed to fail in discriminating promising athletes during the late teenage period (**Figures 2-M** and **2-F**). These results are in line with the study of Larsson et al. (2002) that found no significant relationships between anthropometry and performance level in elite junior XC skiers of 18 years old (Larsson et al., 2002). Our results are also partly in line with a longitudinal analysis of national-level junior speed-skaters monitored between 17 and 21 years of age (de Koning et al., 1994), where no differences in anthropometric and physiological variables measured during the late teenage period were found between athletes who were successful or unsuccessful after the late teenage period, making it difficult to distinguish further talent after the late teenage period.

Absolute and mass-scaled V'O_2 MAX, for males and females, respectively, and maximal ventilation volumes for males were found to be possible parameters during the late teenage period for the discrimination of those who were subsequently selected by the national team from those who were not (**Figures 3-M** and **3-F**) since all the selected athletes showed values within or above the 75th percentile of the entire group at both 17 and 18 years of age. Mass-scaled V'O_2 MAX failed in discriminating the two groups during the late teenage period, even though the body mass of selected athletes did not apparently differ from the rest of the group. Probably, the increasing trend found in anthropometric parameters of males during the late teenage period still acted as a confounding factor, indicating absolute V'O_2 MAX as a more valid indicator of performance in males. However, it was previously shown that absolute V'O_2 MAX values for males (Larsson et al., 2002; Sandbakk et al., 2010b, 2011) and mass-scaled V'O_2 MAX values for females (Larsson et al., 2002; Sandbakk et al., 2010b, 2011) are better related to modern XC skiing performance. When considering previous literature concerning national to world-class level XC skiers, it was shown that absolute V'O_2 MAX while roller-skiing to exhaustion ranged from 4.7 ± 0.7 to 5.2 ± 0.5 L·min^{-1} in male juniors of 18 years old, depending on the technique used (Larsson et al., 2002; Sandbakk et al., 2011). Further in an athlete's career (between 23 and 25 years), V'O_2 MAX values of 5.5 ± 0.3 to 5.9 ± 0.5 L·min^{-1}, and maximal ventilation values from 192± 20 to 204 ± 14 L·min^{-1} were found in male elite XC skiers, depending on the technique and protocol used (Sandbakk et al.,

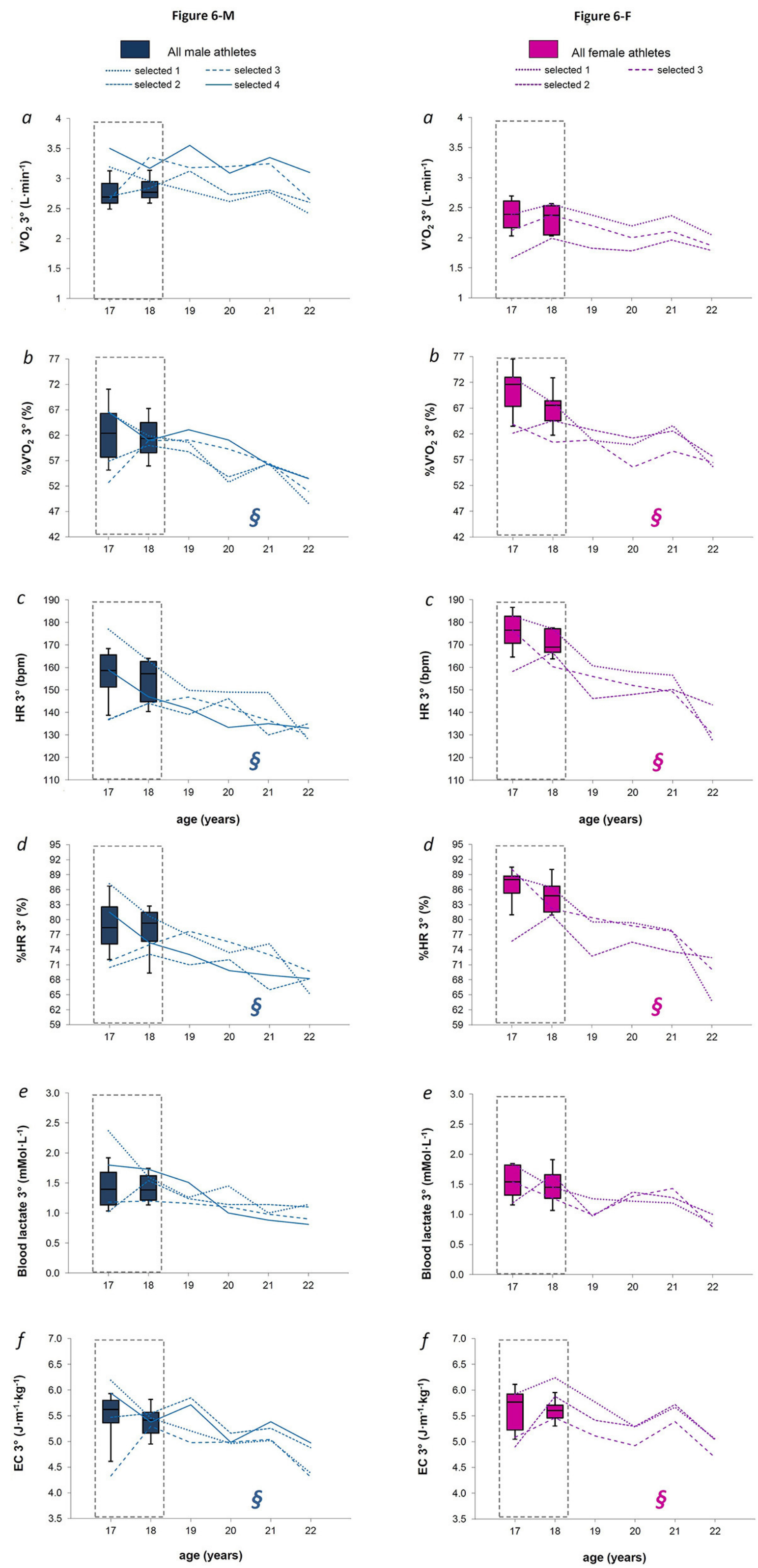

FIGURE 6 | Figures 6-M and 6-F. For males and females (Figures 6-M and 6-F, respectively), the box plot represents medians, 9, 25, 75, and 90th percentiles of the values measured at 3° of treadmill incline (3°) for absolute oxygen consumption (panel *a*), relative oxygen consumption (panel *b*), absolute heart rate (panel *c*),

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FIGURE 6 | relative heart rate (panel *d*), blood lactate concentration (panel *e*), and energetic cost of diagonal skiing (panel *f*) measured over the late teenage period (data in dotted-lined boxes) in the entire group. In each panel, the line plots represent each selected athlete from 18 to 22 years of age. **§** indicates a likely effect of age after the late teenage period.

2010b; Losnegard et al., 2013; Andersson et al., 2014). These data confirmed that a combination of high values of absolute oxygen V'O_2 MAX together with high maximal ventilation volumes are features that describe high-level male XC skiers.

Few of the physiological parameters measured at the VTs intensities or at sub-maximal mechanical intensities (3 and 6°, respectively) were found to possibly discriminate further talent from an early age (**Figures 4-M, 4-F**, **5-M**, and **5-F**). Specifically, all the selected males showed higher absolute oxygen consumptions at VTs, while all selected females showed a later occurrence of VTs than the entire correspondent group. These findings underlined the importance of aerobic capacities in predicting further performance in XC skiers of both sexes and are supported by previous data about elite junior XC skiers. Indeed, significant correlations were found between absolute oxygen consumption at OBLA or second ventilatory threshold and XC skiing performance in male athletes (Larsson et al., 2002), or when analyzing the two sexes together (Sandbakk et al., 2011). Also at these intensities, absolute rather than mass-scaled oxygen consumption better correlated with XC skiing performance (Larsson et al., 2002; Sandbakk et al., 2011). All these findings indicate an advantage for heavier XC skiers in modern XC skiing performance, due to the elevated requirements of speed and power outputs.

Contrary to what was hypothesized, skiing economy did not result in a discriminating factor between groups (**Figures 2** *e,f*, **3** *e,f*), in both sexes. The available literature indicated that skiing economy was one of the most important determinants of XC skiing performance, being able to distinguish high-level from recreational XC skiers (Ainegren et al., 2013; Zoppirolli et al., 2015) and world-class from national-class athletes (Sandbakk et al., 2010a,b), but also being related to differences in performance capacity within homogeneous groups (Millet et al., 2002; Sandbakk et al., 2013). However, the available data are about XC skiers older than 23 years, while no studies analyzed the longitudinal development in skiing economy in younger XC skiers. From our results, skiing economy is most likely not indicative of further XC skiing performance in high-level adolescent athletes, but it decreases significantly after the late teenage period in selected athletes. This result is in line with a longitudinal analysis on junior speed-skaters (de Koning et al., 1994) which found no difference in mechanical efficiency during the late teenage period between athletes that were or not successful after the late teenage period.

The present study reported a first attempt to evaluate which anthropometric and physiological parameters measured during the late teenage period could help discriminate further talent, in junior XC skiers. Here we analyzed athletes' physiological characteristics during an incremental test to exhaustion performed with the diagonal-stride technique (both upper and lower body involved in the propulsive actions Andersson et al., 2014). However, other types of testing protocols might improve the process of talent selection in junior XC skiers, since strength, power, and technical capacity are strictly linked to modern XC skiing performance, in addition to endurance capacity (Alsobrook and Heil, 2009) in junior XC skiers (Carlsson et al., 2017). It is known that the higher the amount of upper-body involvement in different XC skiing sub-techniques (diagonal-stride vs. double-poling sub-techniques, where the upper body is primarily involved in the propulsion Holmberg et al., 2005), the higher the difference in endurance performance between sexes (Sandbakk et al., 2012a,b), with females underperforming because of their lower upper body muscle mass, strength, and power with respect to male athletes. Thus, the inclusion of standardized upper body strength and power tests, the evaluation of incremental test to exhaustion performed with the double-poling technique, together with the assessment of psychological attitudes might reveal additional useful information for the talent selection process of XC skiers in the future.

LIMITATIONS

This data analysis represents one of the first attempts to analyze talent development and selection in young high-level cross-country skiers. A high number of inclusion criteria were necessary to perform this peculiar observational study, thus reducing the number of athletes included in the data analysis. Even though our findings fit well with some concerns provided by previous literature, these outcomes are difficult to generalize and further research is needed to deepen these aspects about performance on young athletes.

CONCLUSIONS

For the first time, this study presented a longitudinal analysis of anthropometric and physiological characteristics from the junior to senior level (6 consecutive competitive years) in XC skiers. We found that anthropometric parameters were still raised between 17- and 18-year-old males, while females had already ended their growth process before that age. Most of the absolute and relative physiological parameters at maximal stages did not change significantly during the late teenage period in both sexes, except for V'O_2 MAX and maximal heart rate which increased and decreased, respectively, in females. At sub-maximal exercise intensity, we found that V'O_2 at VT2 or moderate exercise intensity increased during the late teenage period in males, while HR at VT2 decreased in both sexes. A progressive decrease in the energetic cost of skiing was found after the late teenage period in selected athletes of both sexes, in relation to improvements of the aerobic pathway. Even though genetic, environmental, and psychological factors were demonstrated to be of particular

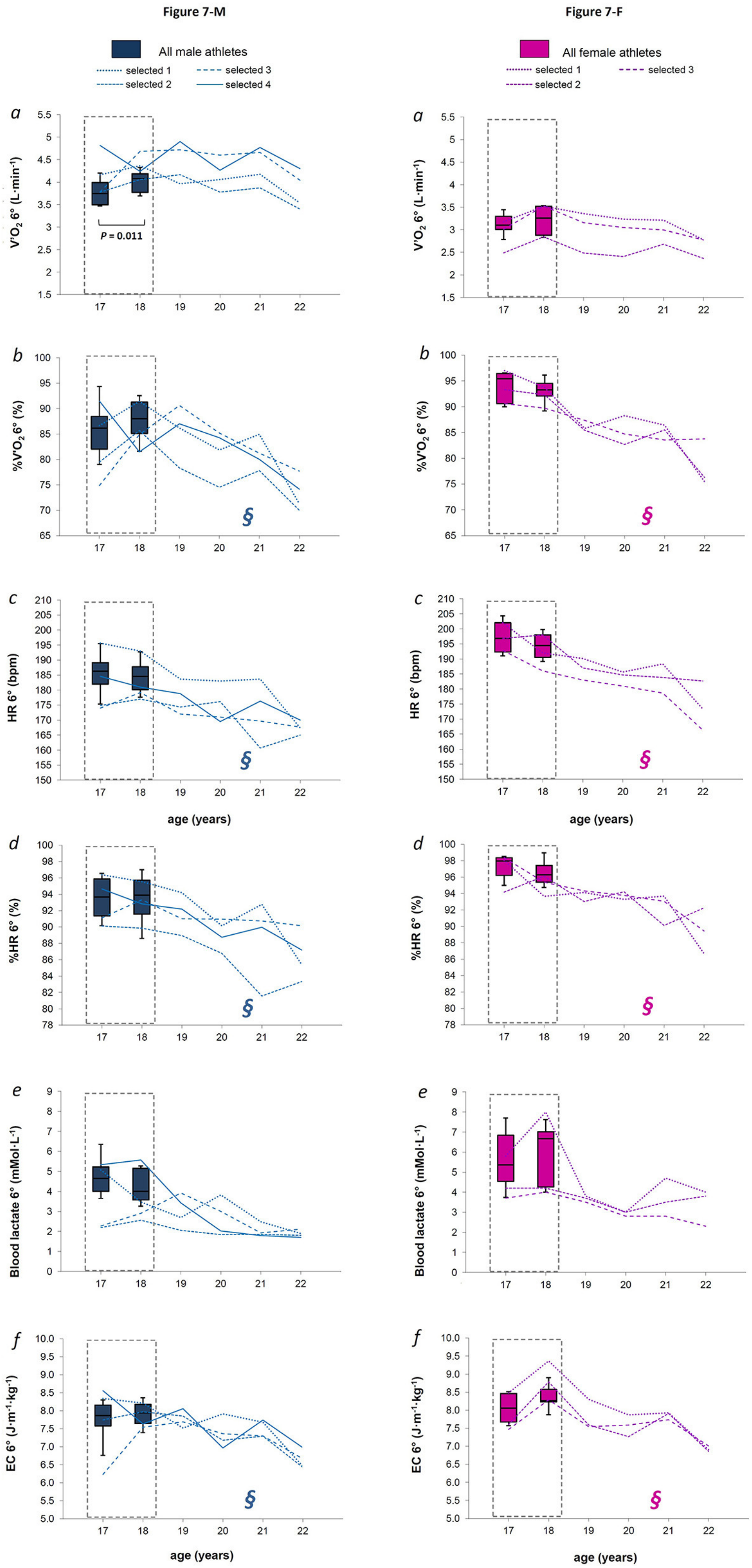

FIGURE 7 | Figures 7-M and 7-F. For males and females (Figures 7-M and 7-F, respectively), the box plot represents medians, 9, 25, 75, and 90th percentiles of the values measured at 6° of treadmill incline (6°) for absolute oxygen consumption (panel *a*), relative oxygen consumption (panel *b*), absolute heart rate (panel *c*),

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FIGURE 7 | relative heart rate (panel *d*), blood lactate concentration (panel *e*), and energetic cost of diagonal skiing (panel *f*) measured over the late teenage period (data in dotted-lined boxes) in the entire group. The *P*-value refers to the statistical age effect during the late teenage period. In each panel, the line plots represent each selected athlete from 18 to 22 years of age. **§** indicates a likely effect of age after the late teenage period.

importance for exceptional athletic performances, we found that some physiological parameters measured during the late teenage period (thus well over the occurrence of peak maturation velocity) could help in discriminating further performance capacity in high-level XC skiers. Since the late teenage period, high $V'O_2$ at maximal stages as well as at the ventilator thresholds' intensity, together with elevated maximal ventilation volumes characterized the male athletes that were further selected to compete internationally. Finally, mass-scaled $V'O_2$ at maximal stages together with postponed ventilatory thresholds' occurrence appeared to be good indicators of further talent in females.

The present study can be considered as a pioneering analysis of talent development and selection in XC skiing. More research should be considered over the next few years and an international board should be created to deepen this matter. A multilateral approach should be considered in the future, both from a performance and a psychological perspective. Strength and power tests for upper body and/or maximal tests using the double-poling technique (relying more on upper body work) could reveal other or better predictors, especially in female athletes. Moreover, evaluations of exercise motivation, stress resilience, and residual trainability should be considered in the future when analyzing talent development and selection in young XC skiers, because of the importance of psychological attributes for exceptional sport performances.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

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

AUTHOR CONTRIBUTIONS

CZ was the head of the research and draft the manuscript. All the authors were involved in the data acquisition, processing, analysis, and collaborated in preparing the text of the manuscript.

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Influence of Line Strategy Between Two Turns on Performance in Giant Slalom

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In alpine ski racing, different line choices can drastically affect turn or sectional performance. The straight-line transition between two turns is the main phase where skiers can gain speed in a race, open their trajectory, or reduce their path length. Between two turns, a skier can foster speed increase by spending more time in a straight line, inducing sharper turning phases (Z strategy). Inversely, speed can be conserved during the entire turn cycle by performing long curved turns separated by a short straight line (S strategy). This research aimed to evaluate the kinetic and kinematic specificities associated with the line strategy and to explore interactions of selected strategy with skier performance and energy dissipation. A mixed-level population of male alpine skiers ($n = 17$) skied a timed giant-slalom course while equipped with specialized force plates and a positional device collecting synchronized normal ground reaction force and position-time data, respectively. Time of edge switch was computed from the force signal as the period with the lowest force application on the outside ski. From positional data, turn cycles were separated into turning and straight-line phases (radius bellow and above 30 m, respectively). Time length, path length in the straight line, speed amplitude, and change in specific mechanical energy were computed for each turn and averaged for each skier. The path length during straight line was used to continuously characterize the line strategy within the spectrum between the Z (long straight line) and S (short straight line) strategy. Path length in the straight line was correlated with the amplitude of speed over a straight line ($r = 0.672$, $p = 0.003$) and relative and absolute time spent in the straight line ($r = 0.967$, $p < 0.001$). However, path length in straight line was not correlated with decrease of speed in the following turn ($r = -0.418$, $p = 0.390$) or time without force application on the outside ski ($r = 0.195$, $p = 0.453$). While higher-performing athletes on the course performed turns during which they dissipated less energy when normalized to entry speed ($r = -0.620$, $p = 0.008$), it appears they did so with variable turn strategies approaches.

Keywords: alpine skiing, performance, trajectory, GNSS, force-plate

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INTRODUCTION

To achieve the lowest possible race time, alpine skiers must continuously adapt their strategy and technique. Skiers perform turns according to their position, speed, and balance (influenced by the previous turn), individual capacity evolving with fatigue (technical, physical, psychological), and environmental factors (e.g., snow characteristics and micro reliefs, steepness, visibility, course setting, ski gear) (Supej and Holmberg, 2019). Some parameters cannot be anticipated before the race, which means skiers must continuously adapt their turn line strategy throughout the race.

In this article, the alpine skiing turn is defined by a straight line (SL) followed by a turning phase (TP). The trajectory and overarching turn characteristics the skiers choose (i.e., "line strategy") can generate substantial differences in turn-time in giant slalom (GS) (Brodie et al., 2008) or on the following sections (Supej and Cernigoj, 2006). Skiers accelerate quasi-exclusively by converting potential energy into kinetic energy during the SL, while aerodynamic and ski/snow friction dissipate energy notably during TP. Energy dissipation characteristics are used to quantify performance (Hébert-Losier et al., 2014) and are commonly defined by the differential of the sum of kinetic and potential energy normalized to skier mass (m) (Supej, 2008; Reid et al., 2009). Since performance is partially dependent on the turns preceding it, normalizing energy dissipation to the velocity at the entry of the corresponding segment (v_{in}) provides a means of characterizing sectional performance ($\Delta e_{\mathrm{mech}/}v_{\mathrm{in}}$) (Supej and Holmberg, 2019). From a mechanical perspective, better turns are described by dissipating less energy via friction while following the most direct trajectory, which maximizes the transfer between potential to kinetic energy (Supej, 2008).

At every turn, skiers must balance between two strategic line approaches (Supej, 2008; Federolf, 2012).

The first line strategy focuses on reducing mechanical energy dissipation throughout the TP by avoiding skidding. This line strategy is typified by "carving" the skis in long arcing turning phases initiated higher on the slope and greater turn radii during the TP (Müller and Schwameder, 2003). It induces longer TP time, typically longer path lengths, an "S"-shape trajectory, and less speed gained during the SL due to less time spent close to the fall line. Barring high-energy dissipation during the TP, the technique should induce a low variation of energy dissipation during the turn. Coaches advise adopting this technique during low-dynamic phases and in flat, high-speed, and straight sections and do not recommend it after periods of high-speed dissipation (for example after heavy braking due to mistakes or cornering) (Lind and Sanders, 2004). The second-turn line strategy is based on maximizing the transfer of potential to kinetic energy between gates by following a trajectory closer to the fall line. Following this line strategy, skiers will typically delay the beginning of a TP and create a long SL between short TP resulting in a "Z"-shape trajectory. Since more time is spent close to the fall line, skiers gain more speed, and dissipate little energy during the extended SL phase. However, the approach is also characterized by sharper turns (i.e., lower radii), which might change ski–snow interactions and induce skidding and associated energy dissipation during the TP. Consequently, this approach is recommended by coaches in steep, turning, and high dynamic sections. Skiers adopting these two approaches could feasibly gain the same turn or sectional performance, with drastically different energy behaviors (i.e., variability in energy dissipation within the turn) during each turn. Theoretically, these two strategies are called "S" and "Z" strategies in this article, respectively, and represent opposite ends of a continuum of performance separated and identified by length of the SL.

Few studies have assessed the interaction between line strategy and performance. Articles focusing on turn line strategy and Δe_{mech} in giant slalom (Supej, 2008) or in slalom (Federolf, 2012) have not presented clear correlations. This result may be linked to the small and homogeneous observed samples or specific factors relating to the course setup (e.g., a small number of gates observed). Moreover, for skiers with higher v_{in} (typical of high-level skiers), increased velocity or preserved energy is more challenging than for other skiers, and the normalization per entry velocity (i.e., $\Delta e_{\mathrm{mech}/}v_{\mathrm{in}}$) effectively quantifies skiing efficiency. Consequently, subsequent investigations presented a very strong correlation between $\Delta e_{\mathrm{mech}/}v_{\mathrm{in}}$ and race time in slalom (Supej et al., 2011) and in GS (Spörri et al., 2018). In the latter example, the authors presented a mechanical model of performance that quantified the weighted contribution of the capacity to gain or maintain speed relative to the previous section performance (i.e., $\Delta e_{\mathrm{mech}/}v_{\mathrm{in}}$) and the trajectory of the skier (as the cumulated distance per turn) (Spörri et al., 2018). Better-performing skiers typically minimized energy dissipation relative to $\Delta e_{\mathrm{mech}/}v_{\mathrm{in}}$, without an association with path length. The authors concluded that potentially the turn may be separated into phases with distinct aims, with the former half of the turn characterized by minimizing dissipation of energy and a shortening of the path length being preferable in the latter. Spörri et al. (2012) reported that a higher altitude of turn initiations and turn ends were associated with a reduction of time on short sections around the analyzed turn—albeit based on only one skier trial. However, while the interaction between line strategy and performance is associated with minimizing sectional energy dissipation relative to entry velocity, SL, and TP specific energy behaviors have never been clearly assessed.

According to Newtonian physics, a skier must apply external force to deviate from rectilinear motion to turn. When a skier is turning with carving technique, a radial force (i.e., in the direction of the center of the turn) is applied and depends on the speed, the mass of the skier, and the turn radius (radial force [$F_{r=}$m·velocity^2/r]). The radial force can be considered as the component of the ground reaction force acting in the direction of the center of the turn. Therefore, to increase this force, a skier can theoretically increase the lateral angulation with the snow and increase the resultant normal reaction force (i.e., the normal reaction force applied to the ski in the ski reference, nSkiRF). The positive correlation between mean nSkiRF value and performance is shown by some studies on direct and indirect measurement (Cross et al., 2019). Moreover, the application of nSkiRF differs with turn trajectory, radius (Nakazato et al., 2011), and skier level (Supej et al., 2011). According to the radial force equation above, at equal entry speed, the "Z"-shape trajectory strategy (i.e., associated with smaller turn radii during TP) will require higher nSkiRF during the TP, necessitating greater muscular output, and technical management of the ski snow contact (Federolf, 2012). High-level skiers present intrinsically better technical (i.e., capacity to carve at shorter turn radii) and physical skills (Vogt and Hoppeler, 2014; Franchi et al., 2019), which could allow them freedom to select the Z line strategy while maintaining ski snow contact with low skidding. The low variation of energy dissipation (i.e., "S" trajectory) technique is associated with carving, more extended turning phases, and longer force application time (Brodie et al., 2008); consequently, time to transfer force from one ski to the other could be shorter. This time without nSkiRF on the outside foot is considered as the edge switch moment and could be related to the line strategy used and the technical abilities of the skiers. In this case, technical abilities may allow skiers to perform complex tasks quicker, apply force more effectively to the snow, and continually adapt their trajectory. The assessed lag between force application and consequences on trajectory could be an interesting parameter of technical level. However, the interaction between force application and energy dissipation strategies has never been directly assessed.

The turn switch (TS) is the event used to separate two turns. Despite appearing to be a key event of strategic decisions for skiers, behavior during this period has attracted less attention in the research. At present, there are several ways to separate a course into individual turns via detection of the TS from kinematic and kinetic markers (Fasel and Gilgien, 2016) and subsequently separate a course into individual turns. In the first instance, the available methods are dictated by the sensors involved during the experimentation: stereoscopic 3D cameras (Supej and Nemec, 2003; Spörri et al., 2016), GNSS (global navigation satellite system) with IMU (inertial measurement unit) (Fasel et al., 2016), or force plate (Schaff et al., 1996; Nakazato et al., 2011). These various sensors detect one or multiple events between two turns. According to various definitions, several events can define the end of a turn, the beginning of the following turn, or the switch event between two turns. In chronological order, the turning radius passes above 30 m (1), the skier stops applying force on external foot (2, corresponding to the ski-edge release), the minimum summated nSkiRF over a given turn cycle (3), beginning of force application on subsequent external foot (4, ski-edge taking), and a turn radius below 30 m (5). The order of these events is stable regardless of the skiers and turns (Delhaye et al., 2019). The time when the turn radius is above 30 m is associated with the duration of the SL and period between Fbeg to Fend is considered as edge switch time. While not tested, the distance traveled by the skier with a radius above 30 m and time without force application will theoretically vary according to the line strategy used. Since the timing of these TS events is feasibly a result of different techniques, biomechanical mechanisms, and/or interaction between them, a better understanding of the timing and energy behaviors during this phase could provide insight into skier performance.

The first aim of the study was to (i) identify the kinetic and kinematic characteristics associated with the line strategy. We hypothesize that line Z strategy (characterize by longer path length in the straight line) is associated with (i.a) shorter path length in entire turn, (i.b) greater speed amplitude during the straight line and the turning phase, (i.c) more energy dissipated during the turning phase and entire turn, (i.d) longer time in the straight line normalized to the entire turn time, and (i.e) a longer time without force application between turns. The second aim of the study was to (ii) evaluate the interaction between selected strategy and performance level. We hypothesized (ii.a) that high-level skiers would be more inclined to use Z line strategy and (ii.b) line strategy would be associated with final race time.

MATERIALS AND METHODS

Participants

Seventeen male alpine skiers participated in this study (mean ± SD: age 28.6 ± 9.3 years, height 179.7 ± 5.7 cm, weight 75.6 ± 9.3 kg). Skiers had mixed performance levels, consisting of recreational club level (not ranked by International Ski Federation [FIS]) to top-ranked current and previous elite world cup competitors (FIS points < 2). Each skier was informed of the content of the study and gave their written consent to participate. The experiment was conducted under the Declaration of Helsinki and was approved by the local ethics committee of the Université Savoie Mont-Blanc.

Experimental Protocol and Data Collection

Following 2–3 familiarization trials of the course while being equipped with the various experimental technology, skiers performed one or two timed runs on a 16-gate giant slalom course. Skiers were instructed to ski as fast as possible while avoiding the risk of falling. The athletes were provided with instructions to prioritize finishing the race and within these constraints reduce the race time as much as possible. The course setting was initially performed by a national ski coach, per a 16-gate GS setup with an average distance of 23 m and an offset of 8 m on a 25° inclined groom slope. Setup was close to competition setup featuring irregularities while avoiding side-slope, jumps, and slope-break during turns. Landmark poles were placed close to the course outside of the grooming area, and gate positions were measured relative to them and to these poles in order to triangulate them at every course setting. Skiers used the same pair of race skis (SALOMON Lab X-Race—Annecy—France; radius: 30 m, length: 193 cm) and were equipped with the same model of ski boots (SALOMON XLAB 140+ WC—Annecy—France). Skiers used their own race suits and other FIS-approved race clothing and protective gear (e.g., helmet, goggles, back protectors).

Throughout the duration of experimentation (30 days), snow quality (hardness, humidity, and temperature) and environmental conditions (temperature, wind, and visibility) were observed. Testing took place during the first 3 h after the resort opening, the slope was groomed every night, and snow cleaning was performed between every run to limit the formation of micro-reliefs. Testing was performed only if the temperature during the preceding night was cold enough to freeze the snow. If these factors were not acceptable, experimentation was delayed until the conditions stabilized. Skiers were equipped with onboard validated force plates (Falda-Buscaiot et al., 2016). These force sensors (Sensix—Poitiers—France) 1400 gr per foot and raised the skier by 6 mm. The reaction force normal to the ski on the outside foot (nSkiRF) was amplified and recorded at 200 Hz. The power supply and acquisition gear were placed in a hip bag for a total weight of ∼1 kg. Calibration to body weight was performed by lifting each foot successively while being fully equipped with the technology and equipment. The calibration procedure was performed on the same flat hard surface before the start of the race. Position and doppler speed were recorded by a synchronized GNSS/IMU unit (MacLloyd—Paris—France) with factory fusion computations recorded at ∼10 Hz mounted on the hip. Race time was measured with a FIS approved laser cell system (Tag-Heuer—La Chaux-de-Fonds—Switzerland), which was used as the top level performance variable in the subsequent analyses (i.e., better performance = lesser course time).

Data Processing

Only the best performance (fastest time) was used for analysis, with the first turns of the race containing skating steps excluded. All the data analyses were performed using Matlab version R2019a (MathWorks—Natick—USA). To synchronize GNSS/IMU with a force plate, skiers hit the snow with their skis before and after the race to create acceleration and nSkiRF peak. Using these acceleration and force peaks, all data from force plate and GNSS/IMU were interpolated to resample data at 200 Hz. The "makima" method was used to perform a smoothing interpolation (with less undulation than "spline").

Four TS events were computed (**Figure 1**): two events from nSkiRF data and two from GNSS positional data. End of force application of the outside foot (F_{end}) and beginning of force application on the outside foot (F_{beg}) were detected on a 12-Hz low pass-filtered nSkiRF signal. The typical nSkiRF pattern on the outside ski during a turn is composed by a clear increase, a plateau, and a decrease (**Figure 2**); two consecutive patterns are separated by a period of low force application. Events on the force data were determined using the Perceptually Important Point method (PIP) (Fu et al., 2007). PIP is based on geometrical detection of the furthest vertical distance between data and a line between the endpoints of the interval. This computation is repeated five times to obtain the 7 PIPs (**Figure 2**). PIP6 and PIP2, respectively, represented F_{end} and F_{beg} events. All points were checked manually to ensure they corresponded to the end of the main decrease of force and the beginning of the main increase of force. The lag time between F_{end} and F_{beg} represents the switch between ski edges. The two events computed from positional data are the moment the turn radius passes above 30 meters ($Traj_{>30}$) and under 30 m ($Traj_{<30}$), corresponding to the end of the previous and start of the next turning phase, respectively (Spörri et al., 2012). Longitude and latitude positional data

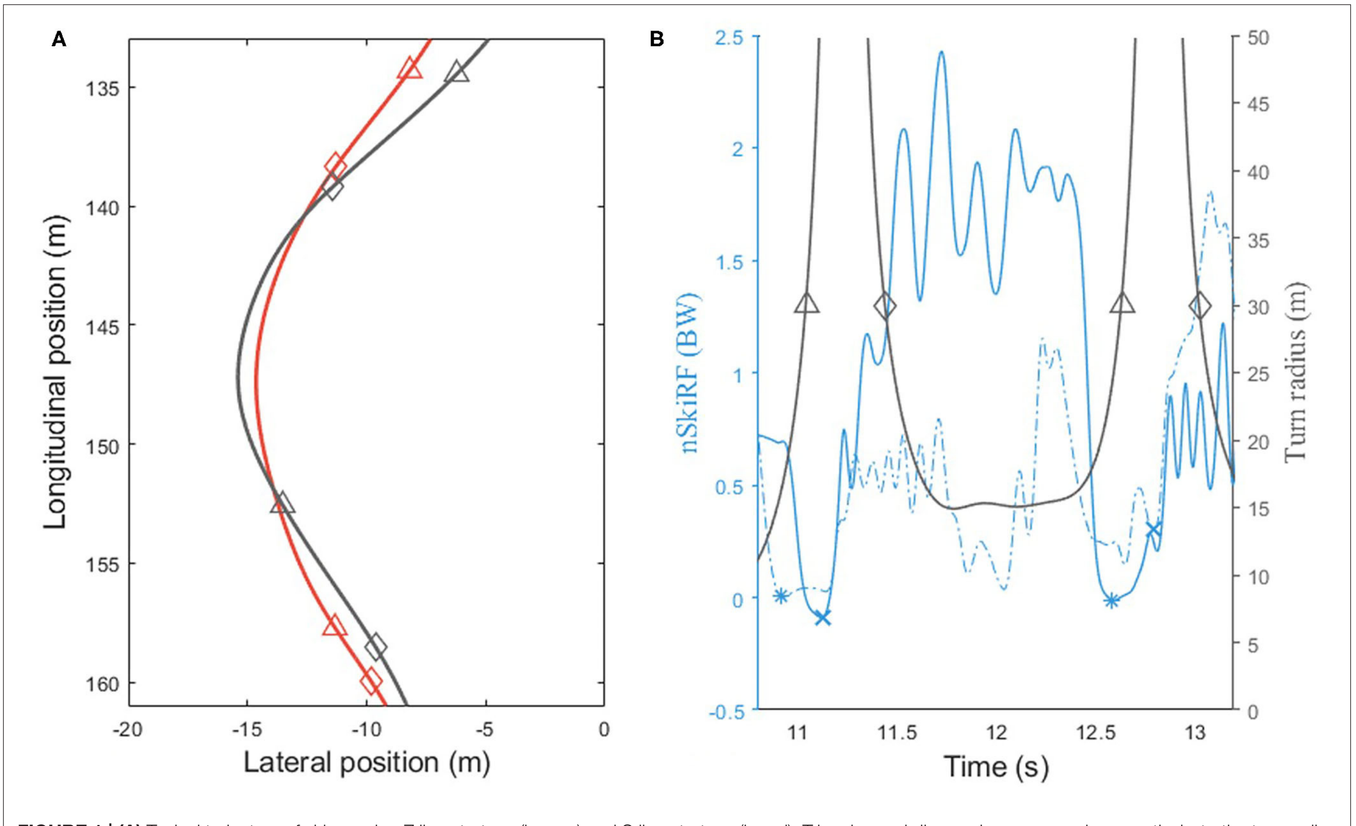

FIGURE 1 | (A) Typical trajectory of skiers using Z line strategy (in gray) and S line strategy (in red). Triangles and diamonds correspond, respectively, to the turn radius passing above 30 m ($Traj_{>30}$) and under 30 m ($Traj_{<30}$), corresponding to the start and end of the straight line. **(B)** Typical evolution of the turn radius (in gray) and normal force applied to the ski (in blue) during a turn. Filled and dashed lines correspond, respectively, to the right and left foot; stars and crosses correspond to the end and beginning of force application.

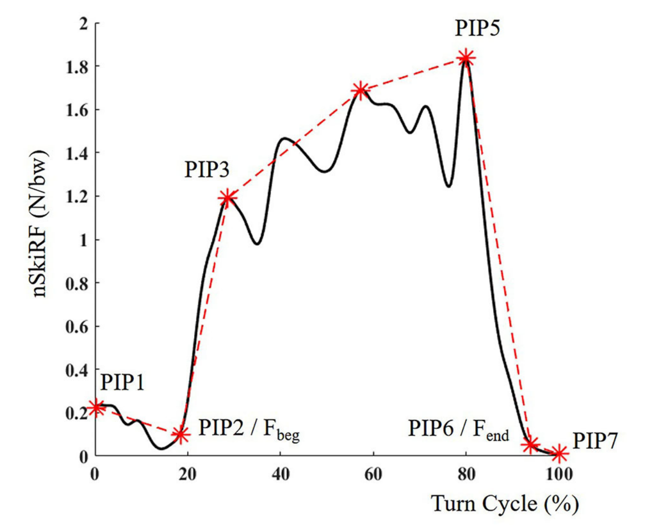

FIGURE 2 | Typical detection of beginning (Fbeg) and end (Fend) of force application on outside foot nSkiRF signal (in body weight BW) during a turn expressed in percentage of turn cycle.

were converted into the Ellipsoid plane using WGS84 standard transformation. All radius and speed relevant parameters were computed using 2D data (longitude and latitude), and path length was computed in the 3D plane (longitude and latitude and altitude). Positional data were smoothed using a Savitzky–Golay filter (order 2, 1-s window). The radius was computed by circle fitting using the Pratt method (Pratt, 1987) (0.3-s window). Automatic detection was performed when the radius crossed the 30-m threshold, and in the case of multiple crossing at the TS last event was retained. The path length was computed as the cumulated displacement in all axes. The lag between $Traj_{>30}$ and $Traj_{<30}$ represents absolute time in SL (T SL in ms). Percentage of the turn in SL (T%SL in %) was defined as T SL relative to the sum of T SL and time of the following TP. The path length is computed for the SL and the sum of the SL and the following TP (Path SL+TP in m). Path length during edge switch was computed using the same approach (Path edge switch in m).

Speed was computed by the GNSS/IMU unit by Doppler measurement related to satellite motion. This computation method is more accurate than derivation of position. To compliment SL and edge switch detection, the amplitude of speed during the SL was computed as the difference between the minimum and maximum speed in the SL (ΔSpeed SL) and for the entire turn (ΔSpeed SL+TP).

Based on positional data, mechanical energy was computed at each point of the race as the sum of potential and kinetic energy, relative to the body mass of the skier (i.e., specific mechanical energy Supej, 2008; Supej et al., 2011). The change in specific mechanical energy was calculated for the following sectional divisions and normalized to the velocity of the first point ($\Delta e_{mech}/v_{in}$): SL ($\Delta e_{mech}/v_{in}$ SL), TP ($\Delta e_{mech}/v_{in}$ TP), and SL + TP ($\Delta e_{mech}/v_{in}$ SL+TP). Finally, race time is considered as the macroscopic indicator of skier performance level and $\Delta e_{mech}/v_{in}$ SL+TP$\Delta e_{mech}/v_{in}$ SL+TP is considered as the instantaneous performance level indicator.

Statistical Analysis

Normality of each parameter was tested using the Shapiro–Wilk test except course time which approaches an expected flat distribution. To evaluate the first aim of the study (i.e., assess the kinetic and kinematic characteristics associated with the line strategy), the correlation between path length in SL and kinematic turn parameters (absolute time in SL, time ratio, speed amplitude in SL, speed amplitude in entire turn, path length in entire turn and $\Delta e_{mech}/v_{in}$ in TP and during entire turn, time without force application) was tested using Pearson coefficient (r), the mean of skier turn cycles ($n = 17$). The second aim of the study regarding the interaction between line strategy and performance was also tested via correlation of straight-line length and race time ($n = 17$).

A hierarchical linear regression analysis was performed to determine whether the line strategy (assessed via the path length in SL) parameter improved the performance prediction provided by $\Delta e_{mech}/v_{in}$ SL+TP. This parameter is already defined in previous literature as a predictor of performance and thus was first forced into the regression. The adding of path length in SL in the equation is tested in a second step to test its influence on race time prediction. Coefficient of determination (r^2) and change in r^2 (Δr^2) between models were calculated. All descriptive data were expressed as means ± standard deviation (SD), and all statistical analyses were performed on JASP (Version 0.13.1—Amsterdam—Netherlands) with an alpha level set at $p = 0.05$.

RESULTS

Mean course time was 29.47 s (SD: 1.85, min: 26.37, max: 34.61), the difference between the minimum and maximum time (i.e., 8.24 s). Once skating steps were removed, 185 turn cycles remained for the final analyses. Correlations between path length in the straight line and kinetics or kinematic parameters of the turn are reported in **Table 1**. T%SL (mean: 32.9%, SD: 4.32%, min: 26.78% max 43.58%) is well-correlated with the path length in SL ($r = 0.967$, $p < 0.001$).

Secondly, mean path length SL is computed for each skier during the race. The mean path length in SL of the population was 8.96 m (SD: 1.16, min: 7.71, max: 11.67). Correlations between race time and path length in SL ($n = 17$) are presented in **Figure 3A**. Correlations between race time and specific mechanical energy dissipation ($n = 17$) are presented in **Figures 3B,C**. There was a moderate relationship of $\Delta e_{mech}/v_{in}$ during turning phase ($r = -0.505$, $p = 0.041$) and entire turn ($r = -0.620$, $p = 0.008$) with race time.

The results of the hierarchical linear regression are summarized in **Table 2**. To assess the predictive power of the model, F and F change values were computed; the root mean square error ($RMSE$) of the predictive model (i.e., square root of the differences between observed and predicted race time values using full equation) was calculated to evaluate the accuracy of predicted race time in comparison with $\Delta e_{mech}/v_{in}$ SL+TP alone; the p-value indicates the significance of the model

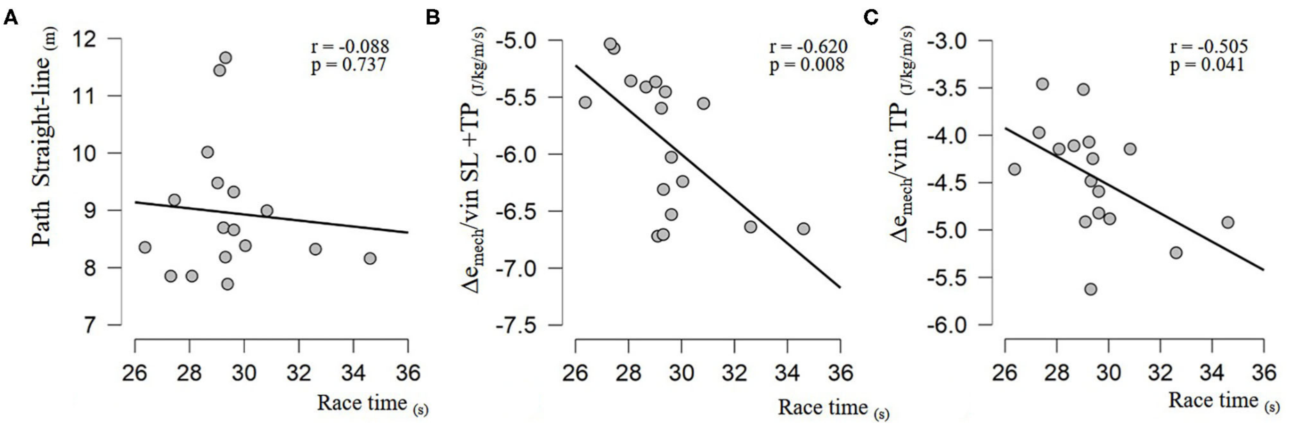

FIGURE 3 | Correlation between race time (in seconds) and **(A)** path length in straight line (radius pass above 30 m), and **(B)** specific mechanical energy relative to entry velocity, respectively: during the turning phase (radius below 30 m), and **(C)** during the entire turn (from the beginning of force application on the outside ski to next one).

TABLE 1 | Correlation tests between path length in straight line (Path SL), and kinetic and kinematic parameters of the turn.

	r **Pearson**	*p*
Path SL+TP (m)	−0.481	0.051
ΔSpeed SL (m/s)	**0.672**	**0.003**
ΔSpeed TP (m/s)	−0.418	0.095
$\Delta e_{mech/}v_{in}$ TP (J/kg/m/s)	−0.223	0.390
$\Delta e_{mech/}v_{in}$ SL+TP (J/kg/m/s)	−0.064	0.808
T%SL (%)	**0.967**	**<0.001**
T SL (ms)	**0.876**	**<0.001**
T Edge switch (ms)	0.195	0.453

Path length in straight line is the cumulative distance traveled by the skiers between two turning phases where the radius is above 30 m. Successive correlated parameters are the path length in entire turn (both straight line and turning phase); speed amplitude during the straight line and turning phase; Δe_{mech}/vin during the turning phase and entire turn; absolute time in a straight line, and relative time to the entire turn time. Edge switch time corresponds to the lag between end of the force application on the outside foot and start of the force application in the new outside foot and edge switch path to the distance travel during this period. Indices of correlation test Pearson's r (r) and p-value (p) were reported.

prediction. $\Delta e_{mech/}v_{in}$ SL+TP was forced in *Model 0*, path length in SL was added in *Model 1*, and path length in SL was finally not included in the model as a significant improvement of race time prediction ($p = 0.301$, R^2 *change* $= 0.047$).

DISCUSSION

Our first result focuses on the links between line strategy and mechanical or kinematic parameters of the turn. Line strategy has to be considered as a continuum characterized by path length in SL. However, the extremes of this continuum are dependent on the course setting and observed population. Consequently, this method only allows characterization of skiers on the same course. The increase in path length in SL was positively linked with longer absolute time in SL ($r = 0.966$, $p < 0.001$), and ΔSpeed SL ($r = 0.554$, $p < 0.001$). There was a trend for a negative correlation between the total path length during the entire turn and path length in SL ($r = -0.481$, $p = 0.051$). These results follow previous works (Federolf, 2012) and corroborate the statement that Z strategy is used by skiers to increase their speed between turns and decrease their total path length. However, a decrease of speed in the following turn was not correlated with the path length in SL ($r = -0.418$, $p = 0.095$). Skiers using the Z line strategy do not necessarily lose their additional speed gained in the SL in the following TP. Absence of significant results could be explained by the capacity of some skiers to conserve their speed even when using a Z line strategy. This capacity could come from a better technical level and better manipulation of the ski angle to decrease friction (Reid et al., 2020). This interpretation is supported by the absence of a relationship between strategy adopted and energy dissipation during the TP ($r = -0.223$, $p = 0.390$). Another explanation could be that some skiers using the S line strategy possibly drift at the beginning of the TP (Müller et al., 1998), which increases delta of specific mechanical energy even with a short path length in SL. This behavior is used when skiers exceed their "velocity barrier" (Supej et al., 2011), in other words when skier's speed is too high to perform the turn imposed by the gate setting.

Absolute and relative time in SL were strongly associated with the path length in SL. However, time of edge switch based on the nSkiRF measurements (i.e., the time between end and start of force application on the outside foot) was independent of the path length in SL. The time of edge switch was not influenced by temporal pressure variation induced by shorter or longer SL. Consequently, the time of edge switch should not be used to quantify the duration of the straight-line trajectory. Rather than turn line strategy, this parameter might be indicative of balance or technical abilities.

The main questions of this study concerned the link between the performance level and the line strategy. In the first instance, path length in SL is not correlated with $\Delta e_{mech/}v_{in}$ SL+TP

TABLE 2 | Hierarchical linear regression model result, specific mechanical energy relative to entry velocity in entire turn ($\Delta e_{mech/}v_{in}$ SL+TP) was forced in the *Model 0*; in *Model 1*, path length in SL was added to *Model 0*.

Model	R	R^2	Adjusted R^2	RMSE	R^2 change	F change	F	p
Model summary of regression analyses to determine prediction of race time								
0	0.621	0.385	0.344	1.566	0.385	9.396	9.396	0.008
1	0.657	0.432	0.351	1.558	0.047	1.152	5.321	0.301

during entire turn ($r = -0.064$, $p = 0.808$). Moreover, a lack of relationship between path length in SL and race time (**Figures 3A,B**) indicates that the use of one predominant strategy is not necessarily linked with overall course performance. Absence of precise results is mainly due to the high variability of the strategy used by medium- and high-level skiers. Among skiers of a similar level (i.e., ranked 5th to 13th with race time between 28 and 30 s), there was substantial variation in SL path length. For example, two skiers performed mean SL path length above 11 m, yet others presented values <8 m. The choice of the strategy used could be determined by various anthropometrical (Haymes and Dickinson, 1980), physiological (White and Johnson, 1991), and technical profiles (Raschner et al., 1995; Müller et al., 2017). However, these interactions have not been recently evaluated on adult skiers.

Finally, according to linear regression results, $\Delta e_{mech/}v_{in}$ SL+TP is negatively correlated with the performance, without a clear contribution of path length in SL. In agreement with previous works (Spörri et al., 2018), line strategy is not a predictor of the performance and does not lead to a decrease in the residuals of $\Delta e_{mech/}v_{in}$ SL+TP correlation. As such, it would seem that independent of the line strategy used, reducing sectional energy dissipation is a key behavior to decreasing race time. These results highlight the presence of skier profiles able to decrease their dissipation of specific mechanical energy, in particular on a given strategy.

In conclusion, the strategy used is associated with differences in kinetic parameters. Increasing the path length in SL (related to Z strategy) induces a higher speed variation during SL, longer turn absolute and relative time spent in SL, and a tendency of shorter length path. However, the strategy used is not linked to time without force application on outside ski between two turns. Overall, the strategy adopted does not appear to be strictly associated with course-level performance of the skiers. The significant dispersion of strategies for the same performance level highlights that radically different approaches can result in similar energy dissipation characteristics. Consequently, it would seem that better skiers possess a profile that enables them to decrease energy dissipation across a variety of preferred and adopted turn strategies.

LIMITATIONS

The top-level performance variable in this study was course time, which represents a macroscopic index and lacks the descriptive information potentially provided by more detailed analyses. Indeed, this parameter is not representative of each turn performance; a high-level skier who made a mistake is considered as the same level as a lower-level skier who did not. Moreover, race time is influenced by snow condition, and even under "acceptable snow conditions," the snow quality variation between subjects could create differences between them. At last, race time is influenced here by the capacity of the skiers to be accustomed to ski gear and experiment devices. Finally, only male skiers were tested, and while we assume our findings apply to female skiers, more research is needed on female skiers.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

Each skier was informed of the content of the study and gave their written consent to participate. The experiment was conducted under the Declaration of Helsinki and was approved by the local ethics committee of the Université Savoie Mont-Blanc.

AUTHOR CONTRIBUTIONS

CD, FH, and MC conducted the data collection. CD, FH, MC, and PS conceptualized the study design and interpretation of the data. CD, MB, and MC contributed to the data analysis. CD drafted the manuscript. All authors revised it critically, approved the final version, and agreed to be accountable for all aspects of this work.

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frontiers in Physiology

REVIEW
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A Narrative Review of Injury Incidence, Location, and Injury Factor of Elite Athletes in Snowsport Events

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Snowsport athletes face a high injury risk both during training and in competitions. Reducing injury incidence is crucial for athletes to achieve breakthroughs. This narrative review aimed to summarize and analyze injury data of elite athletes in snowsports and provide references for injury prevention and health security for these athletes and their coaches. A total of 39 studies that investigated snowsport injury were analyzed in the present study. On the basis of injury data of elite athletes in snowsports events, this narrative review focused on four aspects, namely, injury incidence, severity, location and causes. The findings of this review were as follows. (1) The highest injury incidence was recorded in freestyle skiing, followed by alpine skiing and snowboarding, the majority of which were moderate and severe injuries. (2) The proportion of injury in competitions and during training was similar. However, more injuries occurred in official training during the Winter Olympic Games; by contrast, injury proportion was higher in competitions during World Cup/World Championships. (3) The most commonly and severely injured body parts were the knees (29.9%), head and face (12.1%), shoulders and clavicula (10.5%), and lower back (8.9%). The most common injury types were joint and ligament injury (41.5%), fracture and bone stress (24.4%), concussion (11.1%), and muscle/tendon injury (10.7%). (4) The main causes of snowsport injury were collisions, falls, and non-contact injuries. Snowsport injury was also influenced by the skill level of the athletes, gender, course setup and equipment. Future studies should further explore the influence of event characteristics and intrinsic and extrinsic risk factors on snowsport injury. An injury or trauma reconstruction may be developed to predict athletic injuries and provide effective prevention strategies.

Keywords: Winter Olympics, World Cup, snowsport, injury surveillance study, elite athlete

INTRODUCTION

Professional snowsport racing is characterized by high skiing speed, spectacular jumps and complex skills under cold ambient conditions (Gilgien et al., 2014; Wijdicks et al., 2014; Racinais et al., 2017). However, the spectacular falls, crashes, and injuries of athletes that we regularly see during training and in competitions demonstrate that these elite athletes are highly prone to musculoskeletal injury that may even lead to disability or death (Engebretsen et al., 2010; Weber et al., 2016; Supej et al., 2017; Watanabe et al., 2019). Thus, a systematic injury surveillance is needed for the effective protection of the health of athletes (Soligard et al., 2019). On the basis of this premise, the "sequence of prevention" model (van Mechelen et al., 1992) provides a common framework for injury surveillance and prevention. Injury epidemiology and etiology are considered as the first and second steps for injury prevention, respectively.

Epidemiological studies based on this conceptual model provide information that allows evidence-based decision-making concerning risk levels and the efficacy of preventive and therapeutic interventions (Fuller and Drawer, 2004). These interventions can be described by injury incidence and severity. Furthermore, epidemiological studies should identify the etiology of sports injury (van Mechelen et al., 1992). This inquiry should include obtaining information on how injuries happen (injury mechanisms) and why an athlete may be at risk in a given situation (injury factors). Although an injury may appear to be caused by a single inciting event, it may actually be result of a complex interaction between intrinsic (personal) and extrinsic (environmental) risk factors (van Mechelen et al., 1992; Bahr and Krosshaug, 2005).

The "sequence of prevention" model has become an important reference of injury risk management by the International Ski Federation (FIS). The FIS has published a series of prospective injury reports and has conducted retrospective interviews to identify and prevent injury among elite athletes in snowsports. These studies covered injury epidemiology (Engebretsen et al., 2010; Ruedl et al., 2012; Soligard et al., 2015, 2019; Steffen et al., 2017; Watanabe et al., 2019), mechanism (Bere et al., 2011, 2013; Steenstrup et al., 2018) and causes and factors (Spörri et al., 2012). However, these previous studies were often limited to only one or a few events and disciplines. Only a handful of studies have summarized injury epidemiology and etiology among elite athletes of snowsports (Flørenes et al., 2012; Oslo Sports Trauma Research Center, 2019).

This review aimed to summarize and analyze the data of injury surveillance studies concerning elite athletes in major snowsport events (Winter Olympic Games, Youth Winter Olympic Games, World Cups) from the 2006 to the 2019 season. This review described injury incidence, severity, location and type and identified the factors and causes of these injuries with the long-term goal of preventing injuries.

LITERATURE SEARCH METHODOLOGY

Relevant studies were identified by searching the databases of PubMed and Web of Science from study inception until March 2020. Inclusion criteria were as follows: peer-reviewed, available in full text and published in English. The search terms used were "Winter Olympic, winter sports, alpine skiing, cross-country skiing, freestyle skiing, snowboarding" AND "injury, trauma, injury prevention." Moreover, the authors described injury characteristics and injury patterns and about elite athletes in snowsports. Exclusion criteria were as follows: had duplicate and ambiguous literature; about engineering materials, social science and public health; and about illness in snowsports. A flow diagram describing the detailed search strategy, exclusion criteria and article selection process is shown in **Figure 1**.

INJURY INCIDENCE AND SEVERITY

Injury Incidence

To monitor injury patterns and trends in different FIS disciplines and events, the FIS Injury Surveillance System (FIS–ISS) arranged major events of snowsports (i.e., Winter Olympic Games, World Cups and World Championships) to obtain a complete background data for in-depth studies of injuries. It showed that the risk for injury in alpine skiing, freestyle skiing and snowboarding was higher (Flørenes et al., 2012). Analyzing injury incidence from 13 seasons (2006–2019), the injury incidence in snowboarding, freestyle skiing and alpine skiing can reach about 20.7–68.1 injuries per 100 athletes, 25.4–53.0 injuries per 100 athletes, and 23.5–45.8 injuries per 100 athletes, respectively (Oslo Sports Trauma Research Center, 2019). Compared with other disciplines monitored by FIS–ISS, the injury rate was higher in snowboard cross (11.9 injuries per 1,000 runs) and halfpipe (6.3 injuries per 1,000 runs) (Major et al., 2014), aerials (19.2 injuries per 1,000 runs), halfpipe skiing (23.9 injuries per 1,000 runs), ski cross (18.5 injuries per 1,000 runs) (Flørenes et al., 2010), and downhill in alpine skiing (17.2 injuries per 1,000 runs) (Flørenes et al., 2009). Furthermore, according to the injury data in alpine skiing from three World Cup seasons (2012–2015) (Haaland et al., 2016), the disciplines with the highest injury incidence were downhill skiing (18.1 injuries per 1,000 runs), followed by Super-G (11.1 injuries per 1,000 runs), giant slalom (9.5 injuries per 1,000 runs), and slalom (4.0 injuries per 1,000 runs).

Specifically, we take the last two Winter Olympic Games (WOG), i.e., 2014 Sochi and 2018 PyeongChang, for examples. The previous studies summarized injury incidence in snowsports in the two competitions (**Figure 2**; Soligard et al., 2015, 2019). They recorded higher injury incidence (>15%) in freestyle skiing, alpine skiing and snowboarding than in other events. By contrast, they reported lower injury incidence (<10%) in Nordic skiing (biathlon, cross-country skiing, Nordic combined and ski jumping). Compared with that in the 2014 Sochi WOG, the injury incidence of each sport in the 2018 PyeongChang WOG was lower, except for bobsleigh and skeleton events. A continuous updating of equipment may contribute to the reduction in injury incidence. For instance, skis used in alpine skiing that less shaped and with a greater sidecut radius reduce the self-steering effect (the ski turns by itself if it is edged and loaded) and contributes to less aggressive ski–snow interaction (Kröll et al., 2016a; Spörri et al., 2016). Moreover, a less-shaped ski can increase the turning radius and reduce ground reaction force and kinetic energy while turning (Spörri et al., 2015; Kröll et al., 2016b; (a). Longer skis can increase user comfort and enhance predictability at high speeds, and skis with a reduced profile width can help athletes get off the edge more easily while carving (Spörri et al., 2012). Thus, less-shaped and longer skis with a reduced profile width have been

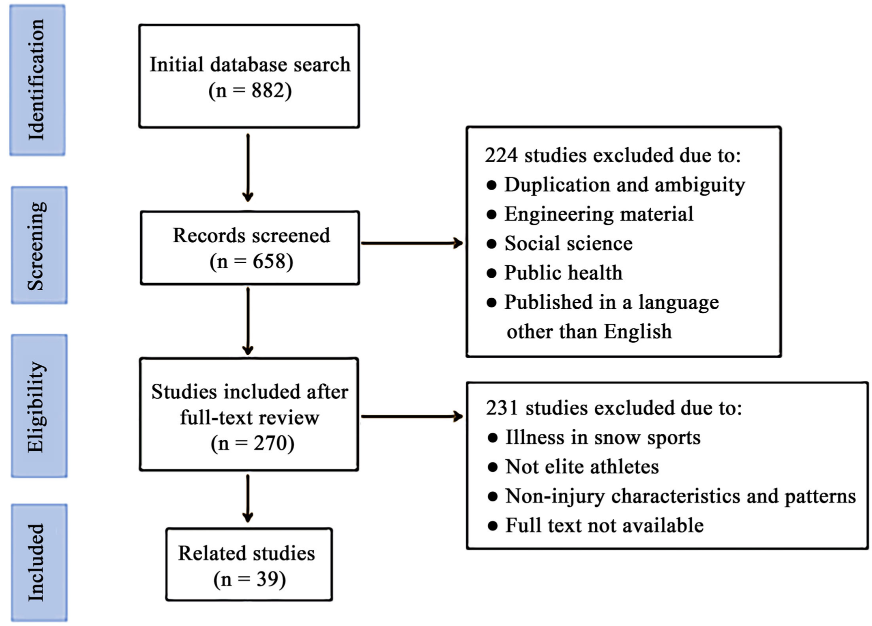

FIGURE 1 | Flow diagram of the literature selection process and the number of articles (*n*) after each stage.

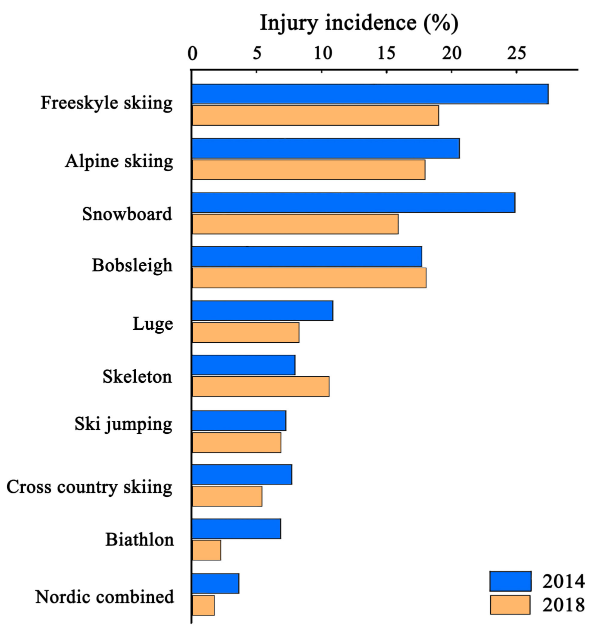

FIGURE 2 | Injury incidence in snowsports during the 2014 Sochi and 2018 PyeongChang WOGs. Blue bars indicate injury incidence in the 2014 Sochi WOG, whereas orange bars denote injury incidence in the 2018 PyeongChang WOG.

proved to have a positive effect on injury prevention (Kröll et al., 2016a,b; Spörri et al., 2016).

Figure 3 shows the injury incidence in each discipline. Compared with that in the 2014 Sochi WOG, the injury incidence in the 2018 PyeongChang WOG was lower in biathlon (2 vs. 7%), aerials (20 vs. 49%), and moguls (5 vs. 25%) but higher in ski cross (24.6 vs. 13.6%) and ski halfpipe (27.5 vs. 25.5%) (Soligard et al., 2019). Changes in injury incidence can be a consequence of changes in the composition of Olympic Games program, environmental factors, course design, competition rules or changes in equipment (Soligard et al., 2019). However, owing to the long interval between two Olympic Games (4 years), injury incidence in WOG might be dominated by only a few factors and with contingency. Also, the difference of injury incidence might simply due to a natural variability of athletes' exposure to risk, and emphasize the value of ongoing surveillance to monitor injury trends over time (Soligard et al., 2015, 2019).

Injury Proportion in Competitions and During Training

Quantifying the proportion of injuries in competitions and during training is essential for developing injury prevention strategies. On the basis of data on injury proportion through all 13 seasons (2006–2019), injury proportion in snowsports in competitions (52.2%) and during training (47.8%) was fairly even (Oslo Sports Trauma Research Center, 2019), but the trend in different events was slightly different. More injuries occurred during training than in WOG competitions. The proportion of snowsport injury during training for the 2010 Vancouver, 2014 Sochi and 2018 PyeongChang WOGs was 53.4, 66.5, and 56.1%, respectively, whereas the proportion in competitions was 41.5, 30.6 and 42.3%, respectively (Engebretsen et al., 2010; Soligard et al., 2015, 2019). In the 2016 Lillehammer Youth Winter Olympic Games (YWOG), 57.4% of snowsport injuries occurred during training (Steffen et al.,

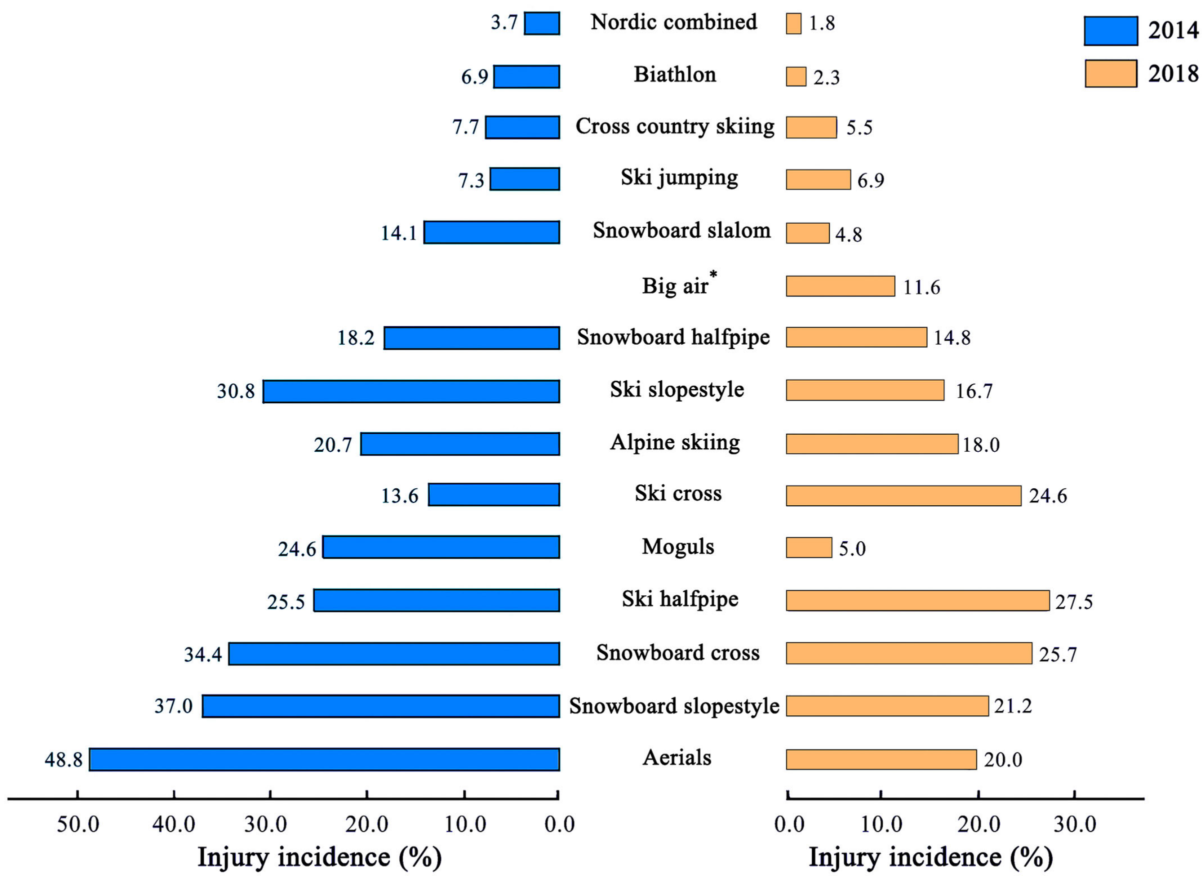

FIGURE 3 | Injury incidence in each discipline during the 2014 Sochi and 2018 PyeongChang WOGs. Blue bars indicate injury incidence in 2014 Sochi WOG, whereas orange bars denote injury incidence in 2018 PyeongChang WOG. *Big air was not included in the 2014 Sochi WOG.

2017). However, in the 2012 Innsbruck YWOG, injuries that occurred in competitions accounted for nearly 60% (Ruedl et al., 2012). A possible reason might be that the training conditions were less competition-specific during this sports event, and the athletes probably had difficulty adapting to a more intense competition. Gradual increases in training intensity to competition level may potentially help reducing ensuing injury incidence in competitions (Ruedl et al., 2012). However, in the World Cup or world championships held annually, more injuries occurred in competitions than during training. In the six seasons (2006–2012) of the alpine skiing World Cup, a total of 577 athletes were injured; 308 in competitions and 269 during trainings (Bere et al., 2014). In addition, a total of 291 acute injuries were recorded in three World Cup freestyle skiing winter seasons (2006–2009). Of the 291 injuries, 74 (25.4%) occurred during official training, whereas 59 (20.3%) injuries transpired from regular training on snow. Four injuries (1.4%) occurred during basic training (not on snow), whereas injuries that happened during trainings accounted for 47.1% (Flørenes et al., 2010). The proportion of injuries during trainings and in competitions might be result of the interval between the two events. WOG is held every 4 years. The time spent training and preparing is longer than in competitions. Accordingly, more injuries occurred during trainings for WOG. By contrast, in events held annually, such as the World Cup and World Championships, athletes may sustain more injuries in competitions than during trainings. On the basis of event interval and characteristics, specific injury prevention strategies for different events are needed to minimize injury incidence.

Injury Severity

Information on injury severity is essential for setting targets for preventive strategies. Uniform definition of terms are also important in snowsport injury surveillance to ensure the comparability of research data (van Mechelen, 1997). Injury severity is classified according to the duration of absence from training and competition (Flørenes et al., 2012; Oslo Sports Trauma Research Center, 2019; Soligard et al., 2019). The International Olympic Committee injury and illness surveillance system defines severe injuries as injuries estimated to lead to absence from training and competition for more than 1 week (Engebretsen et al., 2010; Soligard et al., 2015, 2019). The FIS–ISS classifies injury severity as slight (no absence), minimal (1–3 days), mild (4–7 days), moderate (8–28 days), and severe (>28 days) (Oslo Sports Trauma Research Center, 2019).

In world-class snowsport events, injuries leading to absence from training and competition represent a substantial proportion of all injuries. From 13 seasons (2006–2019), the incidence of injuries leading to absence in alpine skiing, freestyle skiing and snowboarding accounted for 83.6, 80.8, and 78.4%, respectively (Oslo Sports Trauma Research Center, 2019). In contrast, during the 2014–2019 seasons, the proportion of time-loss injury incidence in ski jumping was lower (69.7%) (Oslo Sports Trauma Research Center, 2019). Of the time-loss injuries, the majority was moderate (time loss 8–28 days) and severe (time loss >28 days) injuries, reported over 50% (Oslo Sports Trauma Research Center, 2019). In 2014 Sochi and 2018 PyeongChang WOGs, the injuries resulted in absence for at least 1 day accounted for 44.6 and 45.0%, respectively. Of these, the severe injuries (time loss >7 days) accounted for 56.5 and 49.4%, respectively (Soligard et al., 2015, 2019). Athletes in 2018 PyeongChang WOG incurred fewer severe injuries. International Olympic Committee employed new algorithms to plan the course design of safe but attractive jumps in certain disciplines. It may provide better protection for athletes (Soligard et al., 2015, 2019). More researches are needed to understand the mechanisms and the situations of time-loss and severe injuries. In the 2016 Lillehammer YWOG, 65.7% of the injuries led to absence from training or competition, whereas 25.0% of all injuries resulted in 1–7 days of absence from the sport. During the 10 days of competition, 10 serious injuries (9.3% of all injuries) were registered with an estimated absence from sport for >7 days (Steffen et al., 2017). The estimated number of injuries per 100 athletes per season during the 2006–2007 and 2007–2008 World Cup seasons is shown in **Figure 4** (Flørenes et al., 2012). In terms of severe injuries (time loss >28 days), injury incidence was higher in alpine skiing, freestyle skiing and snowboarding than in ski jumping, Nordic combined and cross-country skiing. Moreover, the rate of severe injuries was higher in ski jumping and Nordic combined than in cross-country skiing (Flørenes et al., 2012). Considering the high speed and vertical drop, jumps and turning around the gate, the high frequency of time-loss injuries and severe injuries may not come as a surprise in snowsports. Future researches are needed to understand the trends and mechanism and develop the appropriate preventive method (Flørenes et al., 2009, 2010; Major et al., 2014).

INJURY LOCATION, TYPE AND FACTORS

Injury Location and Type

The incidence of injury location in FIS disciplines reported throughout 13 seasons (2006–2019), expressed as injured body, is shown in **Table 1** (Oslo Sports Trauma Research Center, 2019). In world-class snowsport events, the most commonly injured body parts were the knees (29.9%), head and face (12.1%), shoulders and clavicula (10.5%), and lower back (8.9%) (Flørenes et al., 2009, 2010, 2012; Major et al., 2014).

Injury incidence of the commonly injured body parts in each discipline in the 2006–2007 and 2007–2008 seasons is shown in **Figure 5** (Flørenes et al., 2012). The most commonly injured body part in cross-country skiing was the lower back (25.0%). By contrast, the highest injury incidence was recorded in the knees in other disciplines (18.9–36.0%). Repetitive back loading in cross-country skiing does not increase the injury risk of the lower back, but the long training hours (>550 h a year) is a risk factor for lower back pain (Foss et al., 2012). In addition, the sagittal configuration of the spine changes in elite adolescent

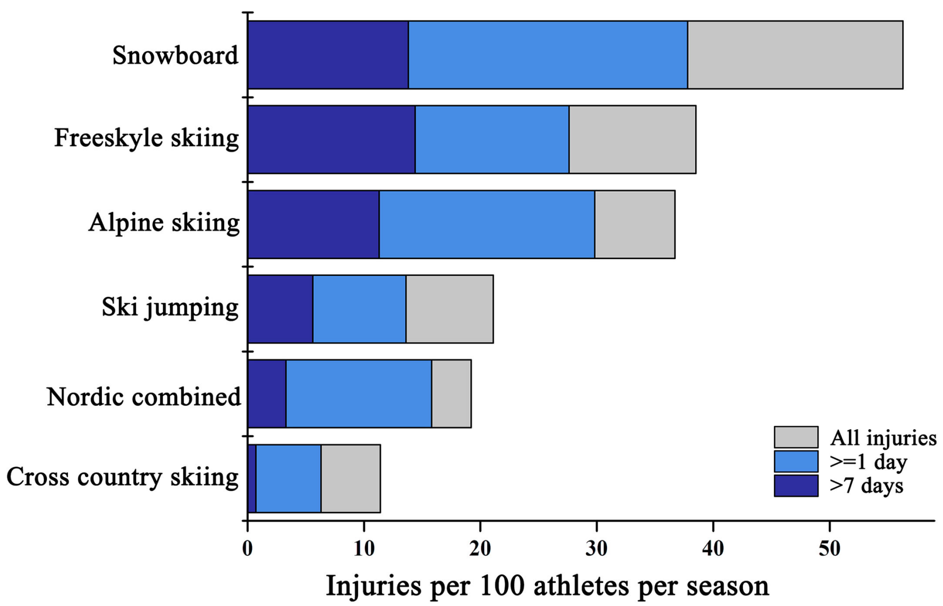

FIGURE 4 | Injuries per 100 athletes per season during the 2006–2007 and 2007–2008 World Cup seasons in alpine skiing, freestyle skiing, snowboarding, ski jumping, Nordic combined and cross-country skiing.

TABLE 1 | Incidence of injury location (%) expressed as body part injured in various FIS disciplines throughout 13 seasons (2006–2019).

Injured site	Alpine skiing World Cup	Alpine skiing European Cup*	Freestyle skiing	Snow-boarding	Ski jumping#	Total
Knees	**41.3**	**36.0**	**32.1**	**16.1**	**41.6**	**29.9**
Head/face	**9.4**	**8.8**	**14.2**	**13.5**	**9.0**	**12.1**
Shoulders, clavicula	**6.1**	**5.0**	**12.0**	**14.3**	**3.4**	**10.5**
Lower back, pelvis, sacrum	**9.2**	**8.4**	**7.0**	**10.7**	**9.0**	**8.9**
Hands, fingers	9.7	13.4	6.3	5.6	0.0	7.3
Ankles	3.8	7.1	5.3	11.2	14.6	7.1
Lower legs, Achilles tendon	9.0	9.6	3.7	2.9	3.4	5.2
Chest (Sternum, ribs, upper back)	1.7	1.7	4.0	4.7	1.1	3.4
Hip/groin	2.1	1.7	4.5	3.3	9.0	3.4
Feet/heels/toes	1.4	2.1	2.3	5.3	1.1	3.0
Wrists	1.2	2.9	2.2	4.6	3.4	2.8
Elbows	0.6	0.8	1.8	2.2	1.1	1.5
Thighs	2.1	1.3	1.4	1.0	0.0	1.5
Neck/cervical spine	0.7	0	1.4	1.6	1.1	1.2
Forearms	0.5	0.4	0.6	1.3	1.1	0.8
Upper arms	0.6	0.4	0.5	1.0	0.0	0.7
Abdomen	0.5	0.4	0.5	0.7	0.0	0.6
Other body parts	0.1	0	0.2	0	1.1	0.1
Total	100.0	100.0	100.0	100.0	100.0	100.0

**Alpine skiing European Cup includes data from six seasons (2013–2019). #Ski jumping includes data from five seasons only (2014–2019). Bold fonts indicate the most common injury types.*

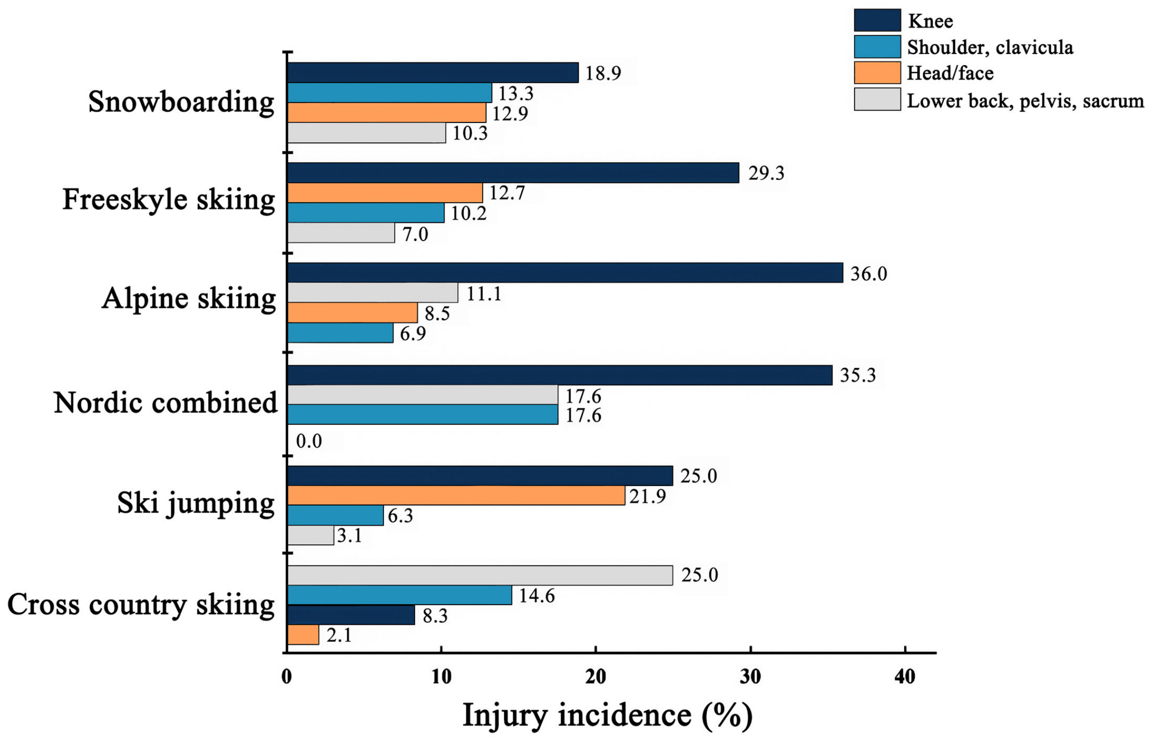

FIGURE 5 | Injury incidence of the commonly injured body parts in different disciplines during the 2006–2007 and 2007–2008 World Cup seasons.

cross-country skiers after 5 years of intensive engagement in the sport (a training volume of 11.7 ± 1.4 h/week). An increase in thoracic kyphosis has been observed in cross-country skiers that may eventually develop to hyperkyphosis over time (Alricsson and Werner, 2006). A strong correlation between lower back pain and an increase in kyphosis of the thoracic spine (p = 0.035) was also found in young elite cross-country skiers (Alricsson and Werner, 2006). Thus, cross-country skiing, as an endurance sport that covers long distances that demands large training volume and involves intensive competition, could contribute to a high injury incidence of lower back injuries (Alricsson and Werner, 2006; Foss et al., 2012).

Matsumoto et al. (2002) conducted a prospective survey and found that the injury incidence of upper extremities in snowboarding is almost twice of that in alpine skiing, accounting for nearly 50% of all injuries. Falls and crashes in training and competition are the main causes of upper extremity injuries in snowboarding (Torjussen and Bahr, 2005; Wijdicks et al., 2014). However, the snowboarders included in the present review were at elite level. Their injuries were not strongly associated with an isolated fall. Injuries in lower extremities among elite athletes associated with strong impact caused by jumping and aerial maneuvers have become more traumatic and prevalent (Wijdicks et al., 2014). Errors in take-off result in jumps that are too high and far and end with a "flat landing" (Davies et al., 2009; Bakken et al., 2011; Kim et al., 2012). A flat landing is described as a landing that occur on a horizontal surface out of the transition slope, thus it cannot provide a graded change from a steep inclination to a horizontal surface. The ground reaction force is more perpendicular to the snowboard and in line with the legs in a flat landing. Thus, a higher force is applied that directly compresses the joints. This condition does not provide the legs sufficient time to absorb the impact. Moreover, the time to decelerate is shorter, resulting in a higher impulse on the leg. This type of landing also increases the eccentric contraction of the quadriceps, thereby increasing the loading to the anterior cruciate ligament (ACL) (Davies et al., 2009; Boden et al., 2010) and compounding the risk of injuries to lower extremities and knees (Wijdicks et al., 2014).

In terms of injury location and severity, the knees, shoulders, head/face and lower back were the most commonly injured body parts, the majority of which were severe. **Table 2** shows the total proportion of moderate (time loss 7–28 days) and severe (time loss > 28 days) injuries in alpine skiing, freestyle skiing and snowboarding throughout the 13 seasons (2006–2019) (Oslo Sports Trauma Research Center, 2019). The proportion of moderate and severe injuries (time loss > 7 days) accounted for 38.8–80.0% in the aforementioned body parts. By contrast, the body parts with a lower injury incidence were the upper arms (0.4–1.0%), forearms (0.4–1.3%), lower leg/Achilles tendon (2.9–9.6%), ankles (3.8–11.2%), and feet (1.4–5.3%), with the proportion of moderate to severe injuries accounting for over 50%. The body parts with low injury incidence may also potentially lead to long absence from the sport. An injury may prevent an athlete from fulfilling his/her potential and achieve breakthroughs. Therefore, stakeholders and researchers should also focus on these body parts.

Table 3 shows the percentage of each injury type in various FIS disciplines reported throughout the 13 seasons (2006–2019) (Oslo Sports Trauma Research Center, 2019). The most common injury types were joint and ligament injuries (41.5%) and fractures and bone stress (24.4%). In alpine skiing, freestyle skiing and ski jumping, nearly half (44.8–49.4%) of the injuries recorded were joint and ligament injuries. Knee ligament injuries were the most common injury type in snowsports (55.6–67.9%). Among these injuries, ACL injuries were the most frequently diagnosis with high severity (Flørenes et al., 2009, 2010; Soligard et al., 2019). In snowsports, spectacular jumps at high speeds are performed on snow surfaces, and technical errors in take-off and landing phases result in falls, collisions and non-contact injuries. In these situations, the force of high impact directed to the joint increases the risk of knee injuries (Major et al., 2014; Soligard et al., 2019).

TABLE 2 | Total proportion (%) of moderate and severe injuries (time loss >7 days) reported in alpine skiing World Cup, freestyle skiing and snowboarding throughout the 13 seasons (2006–2019).

Body part injured	Alpine skiing World Cup	Freestyle skiing	Snowboarding
Knees	**80.0**	**80.8**	**74.2**
Head/face	**61.8**	**55.4**	**45.0**
Shoulders, clavicula	**45.5**	**64.5**	**40.1**
Lower back, pelvis, sacrum	**43.0**	**38.8**	**46.0**
Hands, fingers	30.5	29.1	28.4
Ankles	59.5	55.2	66.5
Lower legs, Achilles tendon	76.5	53.2	73.0
Chest (Sternum, ribs, upper back)	44.4	52.0	51.7
Hip/groin	47.8	50.9	45.2
Feet/heels/toes	92.9	51.7	55.2
Wrists	23.1	50.0	33.8
Elbows	50.0	47.8	53.6
Thighs	69.5	38.9	38.5
Neck/cervical spine	37.5	33.4	40.0
Forearms	60.0	50.0	70.7
Upper arms	71.5	100.0	92.3
Abdomen	80.0	16.6	44.4
Other body parts	1.0	0.0	0.0

Injury location is expressed as body part injured. The bold fonts represent the proportion of moderate and severe injuries in the most commonly injured body part.

Injury Factors

A comprehensive perspective concerning injury factor is needed in developing effective injury prevention strategies. Spörri et al. (2012) conducted interviews with representatives from different expert stakeholder groups in alpine skiing World Cup racing. They perceived 32 risk factors concerning four primary categories, namely, athlete, course, equipment and snow. Interviews with experts (**Table 4**; Spörri et al., 2012) revealed that the top five key risk factors are system ski, plate, binding and boot; changing snow conditions; physical aspects of the athletes; speed and course setting aspects; and speed in general. The injury factors in snowsports can be divided into intrinsic and extrinsic risk factors (van Mechelen et al., 1992; Spörri et al., 2012).

Intrinsic factors include the skill level of athletes, genetic predisposition, sex, and age. Pujol et al. (2007) reported that the incidence of primary ACL injury was higher among alpine skiers who rank in the top 30 in the world (FIS World Rankings). Re-injury and bilateral injury rates were also higher among

TABLE 3 | Percentages of injury types in various FIS disciplines reported throughout the 13 seasons (2006–2019).

Injury type	Alpine skiing World Cup	Alpine skiing European Cup*	Freestyle skiing	Snowboarding	Ski jumping#	Total
Joints/ligaments	**47.1**	**44.8**	**43.4**	**33.8**	**49.4**	**41.5**
Fractures/bone stress	**22.9**	**31.8**	**22.5**	**27.0**	**12.4**	**24.4**
Nervous system/concussion	**8.2**	**8.8**	**12.8**	**12.7**	**6.8**	**11.1**
Muscles/tendons	**10.9**	**9.2**	**9.4**	**11.5**	**19.1**	**10.7**
Contusion	6.2	4.2	8.7	11.7	6.8	8.7
Skin/lacerations	2.8	0.8	0.8	0.9	2.2	1.4
Other injuries	1.2	0.4	1.7	1.6	2.2	1.5
Information missing	0.7	0.0	0.7	0.8	1.1	0.7
Total	100.0	100.0	100.0	100.0	100.0	100.0

**Alpine skiing European Cup includes data from six seasons (2013–19). #Ski jumping includes data from five seasons only (2014–2019). The bold fonts represent the percentages in the most commonly injury types.*

TABLE 4 | Perceived injury risk factors derived from interviews within the basic categories of athlete, course, equipment, and snow (in alphabetical order).

Athlete	Course	Equipment	Snow
Aspects of body temperature	Poor visibility	Binding/plate	Aggressive snow conditions
Athlete's adaptability	Course maintenance during race	Gates (panels and poles)	Changing snow conditions*
Athlete's crash behavior	Course setting in general	Protectors and helmets	Smooth snow surface
Athlete's individual responsibility	Jumps	Racing suits	Techniques in snow preparation
Athlete's race preparation	Level of course difficulty	Ski	
Fatigue	Safety net position and spill zone	Ski boot	
Genetics and anthropometry	Speed and course setting aspects*	System ski, plate, binding and boot*	
Physical aspects*	Speed and topographic aspects		
Psychological aspects	Speed in general*		
Pre-injury aspects	Topography in general		
Skiing technique and tactics			

**Top five key injury risk factors.*

athletes in the top 30. With regard to unfavorable genetic predisposition, Westin et al. (2016) found that compared with athletes whose parents did not suffer from ACL injuries, the odds ratio to also suffer an ACL injury for those with a parent who suffered from ACL injury was 1.95 (95% CI: 1.04–3.65). Sex has different influences on different snowsports. In alpine skiing, injury incidence and severity were higher in males than in females. However, the incidence of knee injury in any discipline was not different between sexes (Flørenes et al., 2009; Bere et al., 2014). The difference in injury incidence between males and females might be related to different skiing patterns (technique and strategy). A study suggested that men are more prone to take risks than women (Bere et al., 2014). In addition, certain extrinsic factors might have an influence on injury incidence and severity. In alpine skiing World Cup, the course is longer, the vertical drop is higher and skiing speed is faster in men's events than in women's events (Bere et al., 2014). Thus, males may have a shorter reaction time than females when facing sudden variations in postural stability and forces acting on the body (Bere et al., 2014). With regard to risk of knee injury, the speed, technical demands and high forces probably overrule any vulnerability factors related to sex (Flørenes et al., 2009). However, no significant difference in injury incidence or knee injury between men and women in snowboarding and freestyle skiing (Torjussen and Bahr, 2006; Flørenes et al., 2010; Major et al., 2014). As noted for alpine skiing, perhaps the technical demands and forces involved in these sports overrule sex factors (Flørenes et al., 2010). With regard to age (biological maturity), in the 2012 Innsbruck YWOG, no significant effect was found on injury risk between athletes aged 14–15 and ≥17 years (Ruedl et al., 2012). However, the majority of the subjects in this study were young athletes. Hence, injury risk in different age groups must be explored. Nevertheless, injuries among young athletes may negatively affect the development of their musculoskeletal structures, potentially resulting in long-term damage (Edouard et al., 2012). This possibility further highlights the importance of preventing injuries in biologically immature athletes.

Extrinsic factors include course setting, discipline and equipment. In alpine skiing, the downhill course is the longest (ranging from 2,000 to 4,500 m) with the highest vertical drop (800 to 1,100 m for males; 450 to 800 m for females) and, consequently, the highest speed (average of 95 to 105 km/h; maximum speed can exceed 140 km/h). These features contribute to high injury incidence in alpine skiing (Flørenes et al., 2009). In freestyle skiing and snowboarding, most injuries occur because of falls and crashes related to jumps, kickers and the halfpipe. In three freestyle skiing World Cup seasons (2006–2009), injury incidence in ski halfpipe and aerials was (18.5–23.9 injuries per 1,000 runs); these are events with challenging aerial maneuvers, and injury incidence in these competitions seems to be at least as high as that in downhill of alpine skiing (Flørenes et al., 2010). Torjussen and Bahr (2006) reported injury risk is 4–8 times higher in big air and halfpipe than in snowboard slalom and giant slalom. In these disciplines, extreme performance, such high jumps and impressive rotations, is the essence of the sport. Technical errors during take-off and landing are the primary cause of injuries (Torjussen and Bahr, 2006; Ruedl et al., 2012). In addition, skis play an important role in injury prevention. The fixation of both feet protects against knee injuries (Sutherland et al., 1996; Rønning et al., 2001) because the ski presumably protects knee ligaments from injuries due to twisting (Pigozzi et al., 1997) and valgus stress (Abu-Laban, 1991). In alpine skiing, skiing speed may be most effectively reduced by increasing the ski–snow friction force in giant slalom and super-G. However, increasing the ski–snow friction force in downhill alpine skiing may be as equally effective as an increase in air drag force (Gilgien et al., 2018). Furthermore, the time and competition schedule are other potential issues. For example, in alpine skiing during the 2012 Innsbruck YWOG, six races were held in eight days, and the athletes often competed in more than one discipline. Physical and mental fatigue may increase injury risk (Ruedl et al., 2012).

CONCLUSION

On the basis of injury surveillance studies and data from elite athletes in major snowsport events, this review found that freestyle skiing, alpine skiing, and snowboarding had the highest injury incidence. Injury incidence was higher in snowboard cross and halfpipe, ski halfpipe, aerials, ski cross and downhill alpine skiing. Moreover, the proportion of snowsport injury in competitions and during trainings was similar in general but different in specific events. Furthermore, the knees, shoulders and head were the most commonly and severely injured body parts. The most common injury types were ligament injury, fractures, concussion and muscle and tendon injuries. The most frequent specific diagnosis with high severity was ACL injury. Finally, the main causes of snowsport injuries were collisions, falls and non-contact injuries due to technical error.

Future studies are warranted to explore further the influence of intrinsic and extrinsic risk factors on snowsport injury. Therefore, innovative study designs, such as expert interviews and injury case reconstruction, are essential complementary tools for investigating the biomechanical mechanism of snowsport injuries, identifying disciplines with high risk of injury and providing evidence-based injury prevention measures for all stakeholders in snowsports. Besides, future reviews and investigations should also include recreational winter sports as well as analyze the incidence of injuries in younger age groups.

AUTHOR CONTRIBUTIONS

WF and LL: conceptualization, project administration, and funding acquisition. CY and YX: literature retrieval, data curation, and writing—original draft preparation. CY, YX, YY, XZ, SZ, and MZ: literature screening. WF, CY, YX, YY, XZ, SZ, and MZ: review and editing. All authors contributed to the article and approved the submitted version.

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MINI REVIEW
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Key Nutritional Considerations for Youth Winter Sports Athletes to Optimize Growth, Maturation and Sporting Development

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Despite a wealth of sport nutrition guidelines for adult athletes, there are currently no nutrition guidelines for youth winter sports athletes. Whilst it may be pragmatic to apply nutrition guidelines for adult athletes to youth winter sports athletes, it is inappropriate. Due to a paucity of research on youth athletes, it is impossible to provide evidence-based guidelines for this population, so careful extrapolation from the theoretical and practical considerations that apply to other athletic groups is necessary. Youth winter sport athletes undergo rapid biological growth and maturation which influences their nutritional requirements. A varied and balanced diet that ensures sufficient energy availability for optimal growth and maturation as well as sporting performance is the cornerstone of youth athlete nutrition and should also allow for youth athletes to meet their micronutrient requirements. In some cases, micronutrient status (e.g., vitamin D and iron) should be monitored and optimized if appropriate by a medical professional. Dietary supplement use is prevalent amongst youth athletes, however is often unnecessary. Education of youth athletes, their parents and coaches on best nutritional practices as well as the risks associated with dietary supplements is vital for their long-term athletic development. Further research in youth winter sports athletes across different stages of growth and maturation competing in a variety of sports is urgently required in order to inform nutritional guidelines for this population.

Keywords: Winter Youth Olympic Games, energy, macronutrients, micronutrients, iron, calcium, vitamin D, youth athlete

INTRODUCTION

Despite a wealth of sport nutrition guidelines for adult athletes (e.g., Thomas et al., 2016), there are only a few review papers for winter sports athletes (e.g., Meyer et al., 2011) and even fewer original research papers on the nutrition needs or practices of youth winter sports athletes. Whilst it may be pragmatic to simply apply recommendations for adult athlete's to youth athletes, there are many reasons why this is inappropriate (see Hannon et al., 2020b for an overview). As a result of ongoing growth and maturation, youth athletes go through many anatomical and physiological changes that impose specific nutritional requirements during their second decade of life (Malina et al., 2004). Nutritional recommendations for youth athletes therefore should not only focus on sporting performance but first meet the requirements for optimal growth and development (Bergeron et al., 2015, Tercier et al., 2019).

Youth winter sports athletes have diverse physiological and metabolic capacities, their respective sporting demands, physiological and metabolic, differ greatly and they compete in a wide variety of conditions. The unique combination of maturity status (Lloyd et al., 2014), sport [e.g., ice hockey (Konarski et al., 2019), ski mountaineering (Praz et al., 2014) or curling (Ainsworth et al., 2000)] and environment [e.g., indoor or outdoor, often cold but sometimes hot, at low or high altitude (Ocobock, 2016)] poses key challenges for practitioners working with youth winter sports athletes. This narrative mini-review discusses some of these key considerations and challenges using the (limited) available literature, and provides some practical approaches with which they can be addressed (**Table 1**). The extant literature was searched using Scholar, PubMed, Web-of-Science, and Scopus from inception to December 2020 using database adapted search strings based on the key-words nutrition, energy expenditure, athletes, youth, winter, sport, and combinations thereof.

Key Physiological Changes in Youth Winter Sports Athletes That Influence Their Nutritional Needs

Youth winter sports athletes (15–18 years) cannot simply be considered "mini adult athletes" despite sometimes competing against adults. Except for the first year of life, adolescence (typically 10–19 years) is the period of greatest growth, maturation, and development across the lifespan (Malina et al., 2004). Growth describes an increase in size whereas maturation describes a more global aspect of physical and cognitive development. More specifically, maturation is the progress toward a biologically mature state, and the rate at which it proceeds is highly variable between different organ systems and tissues (Malina et al., 2004). For example, sexual maturation (the progress toward fully functional reproductive capability) differs from skeletal maturation (the progress toward the skeleton becoming fully ossified) and somatic maturation (the progress toward adult stature; Malina et al., 2004).

There is also a large inter-individual variation in biological age, which may vary (by up to 4 years) from chronological age–the time interval since birth (Lloyd et al., 2014, Malina et al., 2015). Key phases of growth and physical development (i.e., pre-, circa- and post-peak height velocity) lead to many changes such as increases in body mass, muscle mass and blood volume and accrual of bone mass and density all of which influence nutritional requirements (Unnithan and Goulopoulou, 2004). Anthropometric differences between male and female adolescents are the main driver of sex differences in the nutritional requirements of this population, with one exception being iron (see Iron section; Unnithan and Goulopoulou, 2004).

Several major factors must therefore be considered when working with youth athletes: (1) their current maturity status and rate of growth and maturation, (2) their current physiological, metabolic, and psychosocial capacities, and (3) their general life and sport demands (Bergeron et al., 2015, Hannon et al., 2020b). Understanding these factors and their inter-play is a crucial step to developing sport-specific nutritional guidelines (i.e., recommended macro- and micro-nutrient intake) for youth athletes (Bergeron et al., 2015). For example, growth and maturation increase the size of glycogen stores and the relative energy contribution from anaerobic metabolism during exercise, but decreases relative rates of exogenous carbohydrate substrate utilization during exercise (for reviews see Armstrong et al., 2015, Ratel and Blazevich, 2017). These factors may lead to an increased reliance on carbohydrate for energy supply in early compared with late adolescence during endurance (e.g., cross-country skiing), strength/power (e.g., luge), teamplay (e.g., ice hockey) or skill (e.g., curling) sports, but no data are currently available in youth athletes. Although, it is likely that macronutrient requirements will differ for individuals across growth and maturation as well as across different sports macronutrient recommendations are difficult to accurately prescribe without knowing the total daily energy requirements (Bergeron et al., 2015). Indeed, the main focus for practitioners working with youth winter sports athletes is to ensure the energy requirements for growth and maturation are met (Hannon et al., 2020b).

Energy

A youth winter sports athlete's energy intake is provided through the consumption of the macronutrients, carbohydrate, fat, and protein (see Hannon et al., 2020b and, Desbrow et al., 2014 for further information and a more detailed review on macronutrient requirements for youth athletes in general). The energy intake of each athlete is dictated by their total energy expenditure (TEE) which comprises of three components: (1) basal metabolism (the energy required to maintain homeostatic physiology at rest); (2) thermic effect of food (the energy costs of digestion, absorption, transport, metabolism and storage of energy from food and drink), and (3) energy expenditure from planned physical activity and non-exercise activity thermogenesis (Food Agriculture Organization of the United Nations, 2004). In growing youth athletes, a fourth factor should be added representing the energy stored in their increasing body mass (e.g., increased fat-free mass) even though this latter factor is small (<100 kcal) on a daily basis (Prentice et al., 1988, Torun, 2005). Progressive increases in fat free mass (FFM), the most metabolically active body compartment, lead to increases in basal energy expenditure. Recent data from academy footballers showed progressive increases in resting metabolic rate from under 12 years (mean $\pm$ SD; 1699 $\pm$ 195 kcal·day^{-1}) to under 16 years (2042 $\pm$ 155 kcal·day^{-1}) age-groups after which there was no further increase in resting metabolic rate (Hannon et al., 2020a). Comparable resting metabolic rate data are lacking in youth winter sports athletes at different stages of growth and maturation. Before giving specific macronutrient recommendations, it is first essential to understand the typical energy expenditures experienced by youth winter sport athletes.

In healthy physically active humans, exercise energy expenditure is the most variable contributor to TEE (Westerterp,

TABLE 1 | Key messages, practical considerations and important education messages on energy, vitamin D, iron and hydration for the youth winter sport athlete.

Energy	**Importance for the youth winter sports athlete:** • Sufficient energy availability is essential for optimal growth, maturation, and sporting performance (>45 $kcal^{-1} \cdot kg\ FFM^{-1} \cdot day^{-1}$ for adults). **Practical considerations and application:** • The energy requirements of youth winter sport athletes vary considerably. Consider each athlete's anthropometric profile, rate of growth, NEAT, and sporting demands (including training and competition load). • Monitor rate of growth (stature and body mass) and maturation (maturity offset, i.e., time from PHV)-3–4 times per year. • Be alert to any symptoms of low energy availability (RED-S) such as chronic fatigue sensation, low mood, reduced performance, poor concentration, impaired immune system and in females, absence of menarche. **Education:** • Energy density and macro-/micronutrient content of different foods. • Weighing out and visualizing a "typical day's food." • Importance of not missing meals and snacks. • Planning nutrition into their schedule (e.g., when traveling or at school).
Vitamin D	**Importance for the youth winter sports athlete:** • Winter sports athletes are at risk of vitamin D deficiency. This prohormone, alongside calcium, is required in sufficient quantities for bone mineral accrual to ensure optimal skeletal growth and development. **Practical considerations and application:** • Assess vitamin D status and supplement vitamin D_3 accordingly. Vitamin D status can be obtained via a simple finger prick blood sample (and appropriate analysis), or regular blood lab analysis. • If unable to determine vitamin D status a safe dose (typically 800 IU per day−5600 IU per week) may be beneficial to prevent deficiency during winter months. • Consider ethnicity, habitual latitude, and frequency of skin exposure to sunlight. **Education:** • Difficult to be obtained in sufficient amounts through diet. • Importance of (safe) sunlight exposure. • Need for correcting a deficiency through safe sunlight exposure and/or supplementation.
Iron	**Importance for the youth winter sports athlete:** • Iron is an important mineral for many biological processes. Iron requirements increase as a result of (tissue) growth and in females increase further due to menarche. **Practical considerations and application:** • High prevalence of iron deficiency in youth athletes due to insufficient dietary iron intake. • Iron requirements may be increased at altitude, which is relevant for altitude training camps. • Non-haem iron (primarily from non-animal sources) has a low bioavailability making vegetarian/vegan athletes at greater risk of iron deficiency. • Iron absorption is enhanced when consumed with vitamin C and is impaired when consumed alongside tea and coffee. • In case of deficiency iron supplementation should be prescribed by a qualified clinical practitioner. **Education:** • Iron rich foods and their bioavailability. • Food items and combinations that inhibit or favor iron uptake. • Symptoms of iron deficiency (e.g., unexplained fatigue sensation, loss of concentration, diminished performance).
Hydration	**Importance for the youth winter sports athlete:** • There are differences in thermoregulation mechanisms between adult and youth athletes, and among adolescents depending on maturation state. Furthermore, differences in environment, clothing, and metabolic demands between sports lead to differences in heat dissipation and subsequent fluid requirements. **Practical considerations and application:** • Consider environment (i.e., temperature, humidity, and altitude) in addition to clothing. • Appropriate fluid availability (whilst considering environmental temperature) during training and competition, ensuring enough fluids are consumed to prevent excessive dehydration (i.e., >2% of body mass). • Add flavorings and use hot or cold drinks when appropriate to increase palatability and consumption. • Check urine color (aim for pale colored urine). • Check body weight pre- and post-training session/competition to assess fluid losses and determine optimal drinking strategy (including rehydration at 1.5 L fluids per kg body mass lost). **Education:** • Urine color charts to illustrate hydration/dehydration. • Individualized fluid loss assessment. • Optimal drinking scheme for the specific sport.

NEAT, non-exercise activity thermogenesis; RED-S, relative energy deficiency in sport; PHV, peak height velocity. Please see main text for references.

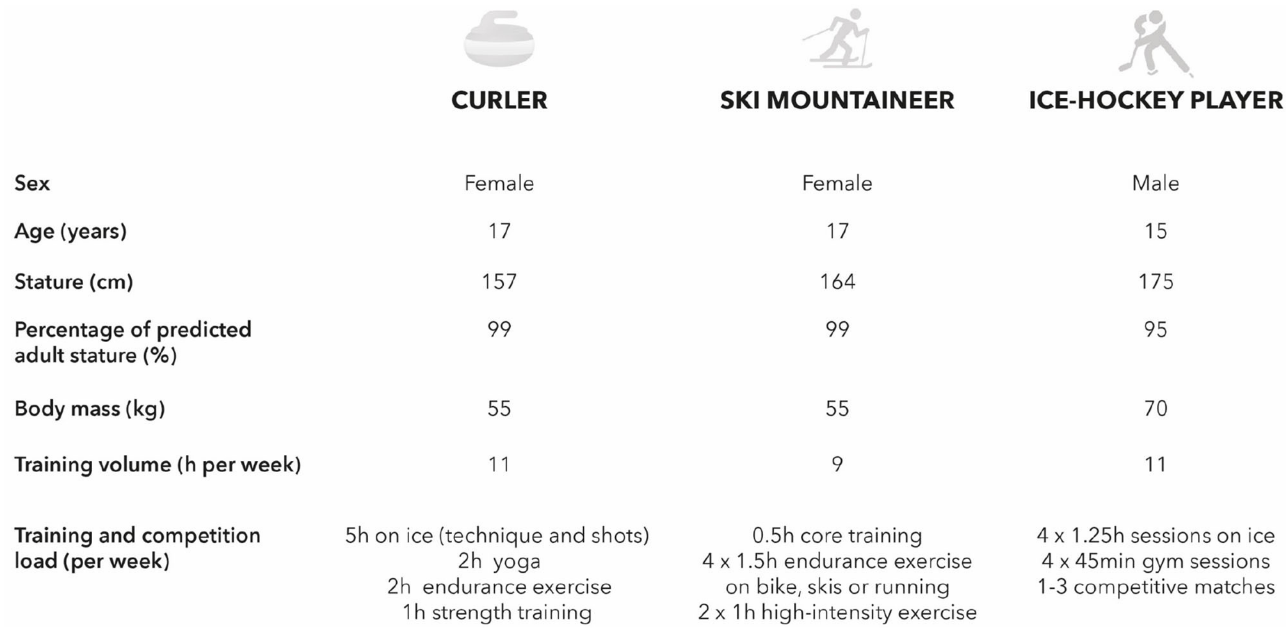
2013), and typically represents between 20 and 60% of TEE (Burke and Deakin, 2000). In athletes, especially endurance athletes, physical activity energy expenditure may become the greatest contributor to TEE (Torun, 2005, Silva et al., 2013). Exercise type, duration and intensity as well as an athlete's anthropometric profile will all influence exercise energy expenditure (and thus TEE). Indeed, there are large differences in the energy cost between different Olympic winter sports (Di Prampero et al., 1976, Tosi et al., 2010, Butte et al., 2018) due to differences in the physiological and metabolic demands of each specific sport (e.g., curling, figure skating, cross country skiing, ice hockey, ski mountaineering). Additionally, the different training loads of each sport change throughout adolescence (Balyi and Hamilton, 2004): for an example see the athlete career pathway by Swiss Olympic (https://www.swissolympic.ch/fr/federations/ftem-sport-athletenentwicklung.html). An overview of the typical training of three Swiss athletes at YOG in Lausanne 2020 is shown in **Figure 1**. Differences in their anthropometric profiles, and training and competition loads between these three athletes likely result in different total energy expenditures and thus energy requirements. Furthermore, training and competition loads may also vary across the annual training and competition cycle and between youth athletes of different ages competing in the same sport, which can lead to differences in total energy expenditure (Hannon et al., 2020c) and thus energy requirements. Across winter sports this results in a large inter-sport and inter-individual variability in total energy expenditure.

As an example, Ekelund et al. (2002) investigated the energy expenditure of youth speed-skaters (age range = 16–21 years) in pre-season and reported mean (±SD) daily total energy expenditure of 4037 ± 693 kcal·day^{-1} (∼53 kcal·kg^{-1}·day^{-1}). Between athletes in this study (Ekelund et al., 2002) there was a difference of almost 3000 kcal in total daily energy expenditure, highlighting the need for an individual approach to energy requirements. No published data exist across different stages of growth and maturation in youth winter sports athletes using the gold standard doubly labeled water technique (Westerterp, 2017). Given the lack of direct measures of energy expenditure across different stages of maturation, precise nutritional guidelines (including macronutrient guidelines) for youth winter sports athletes is therefore difficult to formulate.

Whilst it is difficult to prescribe energy requirements for youth winter sports athletes at both the population and individual levels, it is advised that youth athletes have sufficient energy availability for growth. Energy availability is the amount of energy left for homeostatic physiological functions and growth once physical activity energy expenditure has been deducted from energy intake and is relative to FFM [energy availability = (energy intake–physical activity energy expenditure)/FFM]. Chronic low-energy availability (defined as <30 kcal·kg FFM^{-1}·day^{-1} for adults) may lead to relative energy deficit in sport (RED-S), resulting in impaired growth and maturation of tissues and organs, reduced skeletal bone mineral accrual, increased risk of stress fractures, increased risk of osteoporosis later in life, delayed sexual maturation, disruption of reproductive function (i.e., menstrual dysfunction, low testosterone levels) and a less effective immune system (Loucks et al., 2011). Furthermore, low-energy availability can increase the risk of overreaching (Bellinger, 2020) and is associated with iron deficiency which may exacerbate some of the outcomes of low-energy availability such as sensation of fatigue (Sim et al., 2019). Not only is low-energy availability likely to have a negative effect on a youth athlete's sporting performance and development (Mountjoy et al., 2014, 2018a,b) it may also affect their long-term health. An energy availability of ≥45 kcal·kg FFM^{-1}·day^{-1} is recommended for adult athletes to maintain normal physiological function (Loucks et al., 2011). Considering youth athletes have greater relative energy demands than adults, ≥45 kcal·kg FFM^{-1}·day^{-1} is likely to be the minimum a youth athlete would require. Further research into energy availability especially in at-risk winter sport athletes (e.g., ski-jumpers) is required.

Winter sport training and competition often take place in cold environments and at moderate-to-high altitudes which have many physiological effects relevant to energy needs and intake (Meyer et al., 2011). During the Lausanne 2020 Youth Winter Olympic Games ambient temperatures and venue altitudes ranged from −10 to 14°C and from 400 to 2800 m, respectively. The primary mechanisms for altered energy needs and intake in the cold and at altitude include increases in energy expenditure and appetite suppression (Butterfield et al., 1992, Castellani et al., 2003, Matu et al., 2018). However, the relevance of these to the youth winter sports athlete remains unclear. For example, cold exposure time varies between events and is often counteracted by protective clothing and metabolic heat production during exercise (Bergeron et al., 2012). Furthermore, moderate altitude has been shown to increase resting metabolic rate in some (Woods et al., 2017b) but not all studies (Woods et al., 2017a). These points again highlight the potential value of obtaining accurate energy expenditure data in youth winter sports athletes at different stages of growth and maturation and across a variety of sports in order to formulate research-informed population specific nutritional guidelines. Nonetheless, it is difficult to prescribe energy intake on an individual level given there are many factors that influence a youth athlete's energy expenditure (and thus their energy requirements) including rate of growth, anthropometric profile and training and competition load. Indeed, there is a real risk of being too prescriptive regarding energy intake with youth athletes.

Total energy expenditure is a better starting point to prescribe dietary intake rather than diet macronutrient composition which is the basis of many sport nutrition recommendations (e.g., Desbrow et al., 2014). For example, in the study by Ekelund et al. (2002) the mean total energy expenditure of the youth ice-skaters (mean body mass = 75 kg) performing 1 h of training per day was 4000 kcal.day^{-1}. Using the expert macronutrient recommendations by Desbrow et al. (2014) for adolescent athletes performing 1 h of training per day (3–5 g·kg^{-1}·day^{-1} carbohydrate, 60 g carbohydrate per hour of exercise, 1.2–1.6 g·kg^{-1}·day^{-1} protein and 20–35% energy intake from fat) the recommended energy intake value (3000 kcal) would underestimate the need for intake to cover actual energy expenditure and might lead to insufficient intake.



	CURLER	SKI MOUNTAINEER	ICE-HOCKEY PLAYER
Sex	Female	Female	Male
Age (years)	17	17	15
Stature (cm)	157	164	175
Percentage of predicted adult stature (%)	99	99	95
Body mass (kg)	55	55	70
Training volume (h per week)	11	9	11
Training and competition load (per week)	5h on ice (technique and shots) 2h yoga 2h endurance exercise 1h strength training	0.5h core training 4 x 1.5h endurance exercise on bike, skis or running 2 x 1h high-intensity exercise	4 x 1.25h sessions on ice 4 x 45min gym sessions 1-3 competitive matches

FIGURE 1 | Sex, age, anthropometric characteristics and typical training schedule of a curler, ski mountaineer, and ice hockey player competing in the Lausanne 2020 Youth Olympic Games. The differences in anthropometric profile and training and competition loads between athletes likely result in differences in total energy expenditure and thus energy requirements. Data were kindly provided by the athletes and their coaches via a personal communication to V. Gremeaux.

In summary, eating a varied and balanced diet that ensures sufficient energy availability for optimal growth and maturation as well as sporting performance is the cornerstone of youth athlete nutrition (**Table 1**). In addition, this should also allow for youth athletes to meet most of their micronutrient requirements, although some may require particular attention within this population.

MICRONUTRIENTS

Micronutrients are compounds that are required to maintain normal physiological function. They include minerals, vitamins, and several trace elements such as selenium. Although micronutrients do not directly supply energy for growth, maturation, and performance, they play essential roles in many metabolic pathways. There is currently no evidence to suggest that youth athletes have additional micronutrient requirements compared to their non-athletic peers. Four important principles should be taken into account. First, during growth and maturation there is increased need for some micronutrients; Second, micronutrient need does not linearly scale with increased physical activity energy expenditure; Third, increased physical activity expenditure is accompanied by increased nutritional intake and therefore also micronutrient intake (Heydenreich et al., 2017); And fourth, supplementation with micronutrients should be considered only when direct or indirect information points to a deficiency. Whilst it is essential that youth athletes consume adequate amounts of all micronutrients, there are certain vitamins and minerals that are of paramount importance such as calcium, vitamin D and iron.

Calcium

Calcium is a crucial micronutrient for youth athletes, given that ∼26% of bone mineral content accrues during peak bone mineral content accrual velocity (∼12.5 and ∼14 years old in girls and boys, respectively) and ∼95% of adult bone mineral content is achieved by the end of adolescence (Bailey et al., 1999). Thus, calcium requirements of adolescents are increased as a result of the higher accrual of bone mineral content and during peak bone mineral content velocity, skeletal calcium accretion is ∼300mg per day (Abrams et al., 2004). A number of studies however have reported low calcium intakes in both male and female youth athletes from a range of sports, which are significantly below the recommended daily amounts (e.g., Martinez et al., 2011).

Calcium requirements of adolescents have been described in detail elsewhere (Weaver et al., 2016) and to the best of our knowledge there are no considerations specific to youth winter sports athletes concerning calcium intake. In addition to calcium, the interplay with other nutrients such as phosphorus, magnesium and vitamin D is also vitally important for the formation of the mineral skeleton. Youth athletes are unlikely to be deficient in phosphorous and magnesium (Unnithan and Goulopoulou, 2004), but recent evidence suggests that youth winter sports athletes may be at increased risk of vitamin D deficiency (Zurcher et al., 2018).

Vitamin D

Vitamin D (a prohormone) is a key regulator of calcium homeostasis, with sufficient levels required for calcium absorption (Holick, 2007). Therefore, sufficient vitamin D levels, along with calcium, is crucial to ensure maximal bone mineral accrual in youth winter sports athletes (Cashman et al., 2008). Vitamin D is primarily obtained through dermal synthesis upon exposure to ultraviolet-B (UVB) radiation. During winter months a lack of UVB radiation at high latitudes decreases vitamin D production in the skin (Holick, 2007). Vitamin D containing foods such as liver and eggs contain suboptimal quantities. Indeed, performing training in winter months and indoors (typical of youth winter sports athletes) increases a youth athlete's risk of vitamin D deficiency [serum 25(OH)D < 30 nmol·L^{-1}; Zurcher et al., 2018].

Vitamin D status (insufficient, deficient, sufficient or toxic; Ross et al., 2011) can be assessed using a simple blood test. If an athlete has serum vitamin D concentrations that are insufficient or deficient this can be corrected using supplemental vitamin D_3. These decisions should be taken by a medical doctor and individualized to the athlete. Although a blanket approach to vitamin D_3 supplementation is not advised, a common approach is to supplement athletes with during winter months even without testing vitamin D status (Owens et al., 2018).

Iron

Iron is a trace element involved in many biological processes such as oxygen transport and energy metabolism (Beard, 2001, Hinton, 2014), and also plays a crucial role in the cognitive development of adolescents (Sachdev et al., 2005, Rouault, 2013). The main source is represented by dietary iron, which is poorly absorbed (Beard and Tobin, 2000). During childhood and adolescence, iron requirements increase as a result of tissue growth (Unnithan and Goulopoulou, 2004). Menarche in young women results in increased iron loss through menstruation, increasing iron requirements further in this population (Sandstrom et al., 2012). Exercise can result in iron loss through hemolysis, as well as in urine, stool, and sweat (Peeling et al., 2008). Iron deficiency is highly prevalent amongst adolescent athletes (up to 50% in females; Sandstrom et al., 2012), with inadequate dietary iron intake (often concomitant with inadequate energy intake or a vegetarian diet) often the main cause of iron deficiency (Mattiello et al., 2020).

Symptoms such as fatigue sensation and decreased performance can be associated to iron deficiency with or without anemia (Peeling et al., 2007). Improving iron status in deficient individuals can improve exercise efficiency (Hinton and Sinclair, 2007, Dellavalle and Haas, 2014), fatigue (Pratt and Khan, 2016) and recent evidence suggests that extra iron intake may be necessary for optimal erythropoietic adaptation to altitude (Garvican-Lewis et al., 2018, Hall et al., 2019). Thus, testing of youth athletes who present symptoms associated with iron deficiency (e.g., during regular medical check-up) or who are training at altitude will inform appropriate treatment strategies.

DIETARY SUPPLEMENTS

As discussed, supplementation may be necessary to correct for a clinically defined deficiency (e.g., vitamin D or iron deficiencies) and deficiency is generally the only appropriate reason for supplement use in youth athletes. A varied diet that includes sufficient intake of all the essential nutrients should always be the focus. All essential nutrients can be obtained in sufficient quantities from the diet alone with the exception of vitamin D (see section Vitamin D) albeit others may be challenging to obtain in sufficient quantities in certain diets (e.g., iron and vitamin B_{12} in a vegetarian diet). Nonetheless, the use of dietary supplements such as whey protein, carnitine, branched-chain amino acids, etc. is high amongst youth athletes (Evans et al., 2012). Whilst some of these supplements may provide a performance enhancing effect to some athletes, they come with a risk to health and of an anti-doping rule violation because of the undeclared presence of forbidden compounds in some (Maughan et al., 2004, Maughan et al., 2018). Rather than an attitude focusing on short-term results "potentially" aided by a supplement, youth athletes, their coaches, and parents should have a long-term commitment to good food optimisation which alongside training will provide the foundation for their athletic achievement.

HYDRATION

Thermoregulation is a homeostatic process which regulates body temperature. Growth and maturation leads to decreases in an individual's surface-to-mass ratio and cutaneous blood flow, and increases sweating capacity (Falk and Dotan, 2011, Leites et al., 2016). Meaning, less mature adolescents rely more on radiative and conductive cooling rather than evaporative cooling (peripheral blood redistribution over sweating) to maintain thermal equilibrium (Falk and Dotan, 2011, Desbrow et al., 2014). Given the large inter-individual variability in fluid losses across adolescence, and that dehydration is a common challenge when working with young athletes (Arnaoutis et al., 2015) youth athletes should regularly monitor their fluid needs and consume as appropriate (see **Table 1**).

During exercise, thermoregulation prevents dangerous increases in core temperature. Exercising in hot and humid conditions (e.g., playing indoor ice-hockey) may be a risk for youth athletes as their core temperature seems to rise faster than adults under exercise or environmentally induced heat stress (Falk and Dotan, 2011). When training and competing in extreme conditions (i.e., either hot, humid or cold), youth athletes should take regular breaks and regularly consume cold and flavored fluids in hot conditions (Wilk and Bar-Or, 1996). Training in high altitude can further increase fluid loss at rest and during exercise through hypoxia-induced diuresis and hyperventilation increasing significantly water requirements at altitude to prevent dehydration (Butterfield et al., 1992). In addition, extremely high sweat rates and sodium losses have been reported for some sports such as ice hockey (~1.8 L·h^{-1}) even though the training session was conducted in a cool environment (Palmer and Spriet, 2008, Gamble et al., 2019) highlighting again the effects of clothing on thermoregulation. Ice-hockey players are also at risk of dehydration due to repeated high-intensity efforts and limited fluid availability (Nuccio et al., 2017). It has been reported that junior ice hockey players did not drink enough fluid to prevent body mass losses of <2% during a game (Logan-Sprenger et al., 2011). Due to the large differences in sweat rates (and probably sweat composition) amongst youth athletes competing in different sports and in different environmental conditions, a blanket approach for hydration is unwise and individualized hydration strategies are advised (**Table 1**). It is recommended to monitor hydration status, to provide sufficient drinking opportunities to avoid dehydration and to rehydrate after exercise (e.g., at a rate of 1.5 L per kg body mass lost American College Of Sports et al., 2007).

EDUCATION

Any discussion of nutrition for youth winter sports athletes would be incomplete without mentioning education. Indeed, holistic education is central to practitioners working with youth athletes in their quest to "develop healthy, capable, and resilient young athletes" (Bergeron et al., 2015). Nutrition education should not only focus on increasing nutrition knowledge but also on improving nutrition related skills e.g., budgeting, shopping, food hygiene, preparation, and cooking. This can be delivered in a variety of different formats including on an individual one-to-one basis, group workshops or remotely via photographs, infographics, videos etc. (**Table 1**). Nutrition education should also be extended to parents/guardians of youth athletes given that they are likely to be involved in food selection/preparation etc. as well as in reinforcing educational messages. Being overly prescriptive is by all means to be avoided. Given the extra-ordinary well-orchestrated and generally precisely tuned spontaneous regulation of energy balance, given a reasonably mixed healthy diet, one should part from having faith in physiology and let sensation inform the athlete, all the while accompanying, observing and evaluating, and only if objectively necessary guide and correct in an evidence-based manner.

CONCLUSION

Youth winter sport athletes undergo rapid biological growth and maturation which influence their nutritional requirements. A sufficient energy intake is vital for optimal growth and development but also for sporting development. A varied and balanced diet (that ensures sufficient energy availability) should also allow for youth athletes to meet their micronutrient requirements. In some cases, vitamin D and iron should be monitored and supplemented (if appropriate) under the guidance of a medical professional. In addition to these specific nutritional needs, youth athletes, their parents, and coaches should be educated in sports nutrition. Adolescence is the "prime time" for qualified practitioners to provide athletes, parents, and coaches with information on research-informed nutritional practice. In any case, nutritional considerations for youth athletes should always put growth, maturation and sporting development first and performance second. Further research in youth winter sports athletes across different stages of growth and maturation competing in a variety of sports is now required in order to formulate research-informed nutritional guidelines for this population in keeping with this principle. Key research topics to be addressed include the energy, macro- and micronutrient requirements for youth athletes competing in different winter sports in addition to developing evidence informed educational strategies.

AUTHOR CONTRIBUTIONS

MPH and CD were invited to contribute to this special edition. MPH, JLF, VG and CD planned and drafted this manuscript. NP and BK provided critical revision of the manuscript. All authors approved the final version of this manuscript.

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METHODS
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Method to Investigate Multi-Axis Release Action of Ski Safety Bindings: A New Approach for Testing in Research and Development

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The authors developed and elaborated on a new method to release ski bindings by utilizing an industrial robot to simulate release movement showing a spatial repeatability of ± 0.06 mm. The parametric programming of the release parameters gave free control while executing repeatable release tests. A series of different motion patterns were performed, on the one hand, to test the applicability of the setup to the simulation of motion patterns and, on the other, to check for the impact of the ski deformations like ski deflections within the range of −5 mm to −85 mm, on the safety bindings' release forces. As certain falling mechanisms are related to knee injury, which is the most common severe injury in alpine skiing, this testing method can be used to develop related displacement movements in future. This movements do not necessarily accord with the directional release mechanics of safety ski bindings. The authors specify the developed testing apparatus as device for force measurements in 3D with an accuracy of ± 0.5% in boot-sole-plane. The intention behind this development is to enable faster, more versatile and adaptive testing procedures in R&D.

Keywords: alpine skiing, binding release forces, product testing, force measurement, industrial robot, ski deflection, ski binding boot system, strain gauge

1. INTRODUCTION

Modern ski bindings were designed to protect the tibia and fibula from spiral and bending fractures and the accompanying standards such as ISO[1] 9462, 8061, and 11088 are strongly related to this objective. Alpine ski bindings, the interface connecting the skier with the skis, have not fundamentally changed since the late 1970s (Natri et al., 1999). Basically, modern ski bindings possess a directional sideways release at the toe piece (front parts of the ski bindings) and an upwards release at the heel piece (back parts of the ski bindings). Since this type of safety ski bindings appeared in the early 1960s, traumata of the ankles and tibia fractures decreased substantially, whereas on the contrary knee injuries rates have not decreased substantially. Bearing

[1] ISO-International Organization for Standardization.

in mind that research sources show (Finch and Kelsall, 1998; Langran and Sivasubramaniam, 2002; Pressman and Johnson, 2003a; Ettlinger et al., 2006; Pujol et al., 2007; Burtscher et al., 2008; Johnson et al., 2009; Ruedl et al., 2009; Ekeland and Rødven, 2012; Flørenes et al., 2012; Kim et al., 2012; Sabeti, 2013, Koehle et al., 2002)[2], injuries of the skier's knee could not be substantially mitigated[3]. Furthermore, recent statistics (Greenwald and Toelcke, 1997; Ruedl, 2011; Schulz, 2013, 2016; Ruedl et al., 2014; Shea et al., 2014) demonstrate that knee injuries, especially ruptures of the anterior cruciate ligament *(ACL)* and medial collateral ligament *(MCL)*, are some of the most frequent injuries in alpine skiing with no signs of decline. As a matter of fact, the skier and subsequently the ski boot applies forces to the ski bindings in 3D space, whereas ski bindings react differently to release directions and loading positions. For example, during a backward-twisting fall, the forces apply beyond the boot's heel and the lever, which takes effect on the sideways release of the toe piece, is relatively long. Another example is the forward-twisting fall. When catching an edge in a forward twisting fall situation, the center of gravity of the skier moves forward along the force vector of the mass inertia. This can lead to false negatives[4], because most heel pieces are solely built to release upwards.

Consequently, the most popular falling mechanisms related to knee injuries are as follows: *Slip-Catch, Landing Back-Weighted, Dynamic Snow Plow, Backward Twisting Fall*, and *Boot-Induced Anterior Drawer (BIAD[5])*, which are found well-described in literature (Johnson et al., 1983, 1997; Aune et al., 1995; Koehle et al., 2002; Bere et al., 2011, 2013).

Within these falling and subsequent injury mechanisms concerning the human's knee structure, the valgus-external rotation mechanism and the phantom foot mechanism are the most common causes of structural overload (Ettlinger et al., 1995). Besides, a distribution change from backward twisting falls toward forward twisting falls has been observed (Ruedl et al., 2009) that could be explained by the introduction of shorter skis with narrower turn radii.

Ski bindings testing procedures such as those according to ISO 9462:2014 match with the basic mechanics of modern ski bindings, nonetheless late or no release happens when certain falling mechanisms come into play, despite a conforming SBB setup (Ski-Boot-Binding-System, ISO 11088-2018), which is recommended to be tested with mechanical testing devices by retailers and hiring outlets (Finch and Kelsall, 1998). Thus, the authors decided to develop a new testing setup including multi-axis displacement paths. These shall help to rapidly generate new testing load cases. In turn, this could lead to more elaborate product testing and R&D. For testing current and future binding models and concepts, the motivation was to find a new experimental method not to test a skiing set up according to ISO 9462:2014 or ASTM F504, but to simulate basic release patterns to determine if and how severe deviations in release forces are caused by constraining forces and deformations of ski and binding. Typically, ski binding test machines according to ISO 9462 standards apply combinations of forces and torques to the ski. To investigate forces occurring during multi-plane movements, the authors utilized parametric programming of a six-axis industrial robot to repeatably simulate complex movements of the ski boot's sole surrogate. ISO 11088-2018[6] suggests independently of the tibia method[7] or the skier's weight method, a legit setup range of 30% of binding release torques in the fall direction. This is due to the definition of ±15% steps in binding adjustment table and because of higher false negatives (51% compared to 32%; Ruedl et al., 2016) in binding release in females, lower bindings setups in females, and therefore a gender-dependant binding setup is already discussed by Posch et al. (2017b). To show the capabilities of this new method, several inclinations of the testing boot sole were added to the release movement paths. The testing of pure lateral release motion or lateral outwards-rotation of the heel, despite its importance, was avoided, because it would have led to repeated binding damage as there was no overload emergency stop implemented in the system. Nonetheless, the testing setup enabled the measurement of the forces in 3D occurring in the binding setup during simulating loads similar to those induced by back weighted landing, lateral forces by slip-catching an edge, high ski deflection with regard to the phantom foot mechanism and most of all a freely definable and movable release pivot point.

2. MATERIALS AND METHODS

2.1. General Arrangement

Two types of skis and bindings[8] were used for the tests. An end-effector equipped with strain gauges to measure the occurring forces during motion as well as the bindings' release forces was used instead of a standard ski boot to be placed in the binding. The end-effector was mounted on an industrial robotic arm (*KUKA Quantec series*), which performed the desired motion patterns (**Figures 1**, **2A**, **3**).

[2]Especially Koehle et al. (2002) address the ski binding design as one of the main preventative factors.

[3]Flørenes et al. (2012) have clearly shown the statistical importance of knee injuries, especially during snowboarding, freestyle skiing, and alpine skiing. In addition, Bere et al. (2011) illustrate correlations of several knee injury mechanisms concerning professional athletes and recreational skiers.

[4]Failure of binding release.

[5]The boot induced mechanism occurs when a skier lands off balance to the rear while attempting a jump. Instinctively, the skiers leg fully extends. As a result, the skier lands on the tails of the ski that forces the back of the ski boot against the calf. This pushes the tibia forwards relative to the femur and the ACL tears as a result. A similar mechanism occurs when a stationary skier is hit from behind on the lower leg (usually by another skier or snowboarder). This again applies sudden pressure on the back of the calf, forcing the tibia forwards in a similar manner to that described above with resultant ACL damage: http://www.ski-injury.com/specific-injuries/knee

[6]This standardization primarily addresses the ski sports retailers. See www.iso.org

[7]The tibia method is in the process of being removed from all ISO standards, see ISO 8061-2015 and ISO 11088-2018.

[8]Ski types used: *Atomic SL:2.11* (Setup A) 156 *cm* (used condition) *Betacarve, Dynastar Legend Pro Rider* (Setup B) 186 *cm* (used condition). Contrary ski types and ski binding types were used for reasons of assessing the limits of the testing setup concerning deflection and bending. An *Atomic 614* Race binding (Setup A) has been chosen to represent a standard mid-range priced piste binding as well as *Look Pivot 13* bindings (Setup B). Latter offer a turntable heel piece which is more favored in freeskiing because of its coupling pressure and long elastic travel of the heel piece, which is visible in the pressure curves.

2.2. Ski's Arrangement

The ski was located on two supports, one in front and the other at the end of the ski. The distance between the supports was set at 130 *cm*, while the bindings mounting center lines were positioned about 57 *cm* from the back support (**Figures 1**, **2B**). The ski ends were only fixated sideways for lateral release tests.

2.3. End-Effector

The end-effector consisted of a 15 *mm* custom steel flange in the center to which two 80 *mm* long steel-square-pipes having a wall thickness of 2 *mm* were welded in opposite directions. The front and the back parts of this ski boot-replacing device was composed of an ISO 5355 alpine ski boot sole, which was form-fittingly attached to the steel structure using epoxy resin and additionally secured by four M4 screws each. Summing up, the arrangement was as follows, beginning from the back: heel piece (HP) from an alpine ski boot sole—steel-square-pipe with a wall thickness of 2–15 mm thick and 100 mm long steel flange—steel-square-pipe with a wall thickness of 2 mm—toe piece (TP) of an alpine ski boot. The steel-square-pipes were both equipped with two strain gauge[9] full bridges each located on half way between heel piece and flange, and flange and toe piece, respectively. On both sides, back and front, one full bridge is located in the x-y-plane in order to measure forces acting in the z-direction (indexed as *z*) and the second in the x-z-plane to determine forces in the y-direction (indexed as *y*). A general view of the end-effector design and setup is shown in **Figure 2B**. The steel-square-pipe with a wall thickness of 2 mm was chosen because of its general easy availability, and its well-defined characteristics concerning deformation in combination with the applicability of standard general purpose strain gauges. The flange in the middle of the end-effector caused a mechanical separation of the front and back parts in terms of deformation, i.e., the forces in y- and z-direction, $F_{y,TP}$ vs. $F_{y,HP}$ and $F_{z,TP}$ vs. $F_{z,HP}$, could be detected independently from each other [10]. So, during the tests, not only the bindings' release forces, F_r, should be detected but also it should be reviewed if such a force measuring arrangement could be used for reverse engineering and motion pattern recognition, respectively. In other words, if it was possible to detect the pattern of the executed motion by just analyzing the measured forces. If motion pattern recognition turned out to be feasible and a similar measuring system could be applied to real ski boots, the force signals could be used to analyze the movements of the skier for the purpose of indicating looming falls and associated potential injuries. The full bridges were connected with an amplifier (*MGC Plus* by *HBM*) and an eight-channel data acquisition was used to record the output voltages of the amplifier (*DEWE43* data acquisition operating with the *Dewesoft 7.1* software by *DEWESoft*). A detailed calibration of the whole measuring chain was performed in the laboratory prior to the tests by means of using a primary standard in order to gain accurate coefficients for calculating the forces out of the measured voltage signals. Thus, *BEV*[11]-certified masses were attached to the end-effector for each full-bridge arrangement. The load was increased from small to high masses and decreased vice versa several times in order to eliminate imprecisions in the strain gauge application, inhomogeneities in load-induced deformations of the steel-square-pipes and to assure proper repeatability of the measurements. The obtained calibration coefficients turned out to result in an overall relative accuracy of ±0.5% over the total measurement range for all full bridges. Unfortunately, the full bridge of $F_{y,HP}$ broke down due to bad attachment during the calibration. As this force measurement was of minor interest for the tests performed later and due to the lack of time for repairing until the accessibility to the industrial robot, it was not replaced by a new full bridge.

2.4. Industrial Robot

The end-effector was attached to an industrial robotic arm via the steel flange. The robotic arm (*KUKA Quantec series*), rated for a payload of 210 kg and a repeatability of ±0.06 mm according to ISO 9283, produced the release motions using displacement control. Industrial robots enabled a focus on the test setup itself to simulate the desired release motions by design, rather than requiring the construction of a bespoke, expensive testing apparatus. The visual programming environment *Grasshopper* was utilized, where parametric tool paths can be defined by connecting nodes that expose geometric and mathematical functions. Relevant variables such as the heel rotation and force could be exposed as number sliders, enabling rapid iterations of different load cases, not just in preparation but also on-site during testing. The robot simulation software (*KUKA|prc*) was directly linked to the parametric tool paths within *Grasshopper* so that they could be immediately evaluated, thus enabling an interactive feedback loop. The tool paths were then translated into *KUKA Robot Language* and sent to the robot controller. Using those tools, nearly 200 testing configurations were generated, with further fine-tuning happening on-site (**Figures 2A**, **3**).

2.5. Testing

Basically, the tests should give evidence on the applicability, accuracy and ability to gain detailed information about force distribution in the sole-plane during release action of the newly developed method. So, it was not the aim to develop just a new method to test the functionality of safety bindings according to ISO 9462 but to simulate basic release patterns to determine if and how severe deviations in release forces are caused by constraining forces and deformations of ski and binding. Furthermore, the design of the end-effector and its ability for reverse engineering concerning motion pattern recognition should be tested. As the measurement setup applied to the end-effector presented in this paper was kept rather simple, the motion patterns performed by the robot were kept straightforward, too. As a result, the executed motion patterns neither meet the requirements of ISO standard nor correspond to

[9] Universal general-purpose strain gauge by *Micro-Measurements*, type *CEA-9.6-187UVA-350*. The full bridges were applied to measure shear forces, which results in temperature compensation, independence of location where the force is applied to the lever and in non-sensitivity to torsion.

[10] For example, it could be detected if the end-effector experienced a pure lateral movement relative to the ski, or if a turning motion was applied.

[11] *BEV - Bundesamt für Eich- und Vermessungswesen.*

complex falling trajectories. The motion patterns give an outlook of the capabilities of boot-sole-plane force measurements.

Generally, test sequences on the safety binding's back part, hereinafter referred to as *heel piece opening*, and on its front part, referred to as *toe piece opening*, were performed.

The heel piece opening sequence comprised a rotation around the y-axis, adumbrating the forward lean out-of-balance of a skier, and different deflections in z-direction. The center of rotation was decided to be located at the tip of the boot, i.e., at the front part of the end-effector, for two reasons: first, center of rotations located closer to the heel would cause further bending beyond the preset deflection in z-direction. Besides, further deflections may have caused severe damage of the skis. Second, the center of rotation's location anywhere else but in the shoe tip would result in more complex deformation shapes of the ski than just simple bending, like kinds of s-shaped deformation. The influence of more complex contortion profiles should be avoided as only the influence of different z-deflections on resulting release forces was of interest during the tests. The authors tested release movement with 5 mm (flat ski), 30 mm, and 60 cm z-deflection to see the effect of compressive stress acting on the boot due to ski bending. The displacement in z-direction was measured below the center of the ski boot replacing device from the bottom of the ski surface downwards. A value of $z = 0$ mm meant that the ski was lying freely without any force being applied to it. The deflection values for the testing were chosen according to a related testing procedure of Supej and Senner (2017), who distinguished between three ski-deflection conditions. A flat ski position, a ski deflected according to ISO 9462:2014 referencing a 150 cm support distance with 6 cm deflection, and also a ski-deflection of 6 cm but exceeding the ISO condition by reducing the support distance to 110 cm. In the actual setup, the support distance of 130 cm seemed to be an appropriate fit for both tested ski length (setup A 156 cm/setup B 186 cm). Finally, an additional rotation around the x-axis was applied to the 30 mm z-deflection before the release motion was executed. The heel piece opening tests were only performed with setup A (*Atomic*). For comparison, Ahlbäumer et al. only moved the ski tip 10 mm out of the longitudinal axis to simulate the rotational component while falling without applying any deflection to the ski nor changing the release force direction (Ahlbäumer et al., 1999).

During the toe piece opening test series, falling sequences like BIAD[12], valgus external rotation and Phantom foot mechanism were intended to be allusively be simulated with four different ski deflections. The z-deflections were equal to those described in the heel piece opening sequences ($z = -5$ mm, $z = -30$ mm, $z = -60$ mm) and additionally an extreme ski bending of $z = -85$ mm was examined. For reference, Yoneyama et al. measured up to −30 mm deflection in the ski's rear part while skiing 28 m turns at about 70 km/h (19.44 m/s) (Yoneyama et al., 2010). A rotation of 5° around the y-axis with its center of rotation located in the middle of the front and the back part of the binding should indicate a dislocation of a skiers center of mass to the back. The release motion was a lateral movement of the end-effector's front piece, i.e., a rotation around the z-axis with its center of rotation in the heel part in order to find the release force of the safety binding's toe piece solely. If the center of rotation had been chosen elsewhere, an additional lateral force would have been induced in the binding's back part, too, and a more complex (but more realistic load distribution concerning real falling situations) would have resulted. The test sequences were done with the setup B (*Dynastar-setup*). Next, the influence of an additionally applied rotation around the x-axis of 10° at a z-deflection of −60 mm and y-rotation of 5° on the release forces was checked for both ski setups, A (*Atomic*) and B (*Dynastar*). The toe piece opening test series required an extra lateral fixation of the ski to its supports to preclude the ski from slipping sideways on the supports.

Each test was repeated at least five times and a Student's *t*-test was applied assuming normally distributed measurement samples. The final data analysis was done in post-processing scripts (*Python 3.6.5*). The mean value and its 95% confidence level of the repetitions was calculated to check for significant differences in release forces due to the different ski deflection parameters.

3. RESULTS

3.1. Motion Pattern Recognition

3.1.1. Heel Piece Openings/Forward Bending Release

An example of measured time signals of the acting forces during the test of a heel piece release motion scheme ($z = -5$ mm, no additional rotation around the x-axis) is depicted in **Figure 4**. During this test, no lateral force, i.e., in the y-direction ($F_y = const. = 0$), was applied, so only the recorded forces in z-direction, $F_{z,TP}$ and $F_{z,HP}$, are shown in this figure. The analysis of the time signals emphasized the strength or rather the novelty of the developed measuring setup as the movement pattern could be identified by the interpretation of the forces. The signals presented in **Figure 4** were normalized to the maximum force that appeared during this test because absolute values were of minor interest and would only distract the reader from the focus on the method's capability of reverse engineering. Especially, the forces due to z-deflection could be misinterpreted as representing a skier's mass, but these forces are only related to the stresses and strains in the ski caused by its deformation. The time was also normalized, because the tests were also conducted at different speeds and, interestingly, it turned out that for all tests described in this paper, motion speed does not affect the results. For the purpose of easier interpretation and latter explanations of the time signals, **Figure 4** is divided into four sections, denoted as A to D.

A – boot rests in binding: $F_{z,TP} = 0\ N$, whereas $F_{z,HP} \neq 0\ N$, which was caused by sub-optimal positioning of the boot, i.e., the boot's and the binding's surfaces at the heel portion were not perfectly aligned in parallel in the x-y plane resulting in a slight rotation around the y-axis of less than 1°. However, the heel piece's release value was not affected by this.

B – deflection of the ski in negative z-direction: In the time signal of $F_{z,HP}$, the ski's deflection force can be seen. The higher the peak at the end of section B, the bigger the deflection, the

[12]Boot-induced anterior drawer is a mechanism caused by a backward fall putting severe stress on the knee structures because of the skier's mass inertia in connection with the stiff boot structure, first characterized in Johnson et al. (1983).

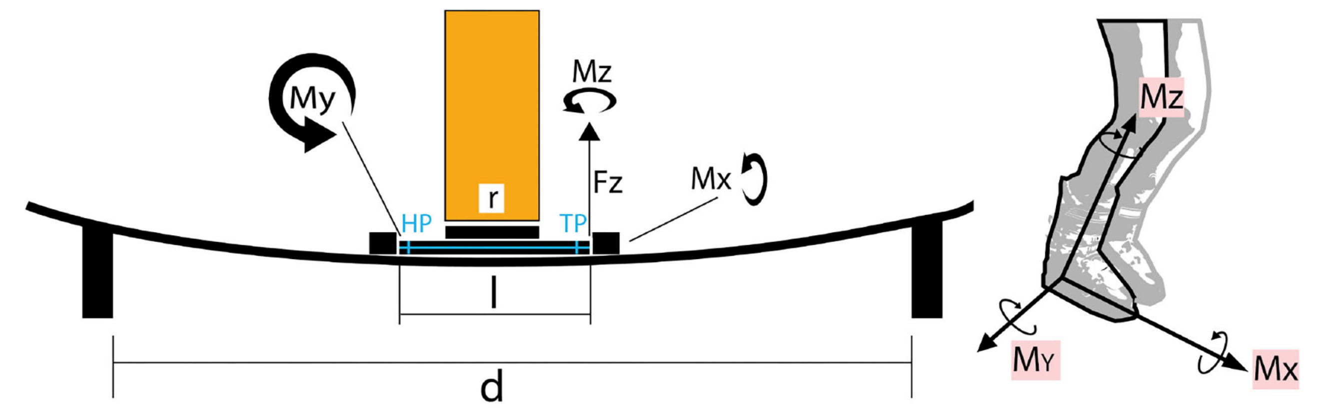

FIGURE 1 | Definition of Cartesian coordinates and of the acting forces and torques, geometry of the test setup: length of ski boot replacing device *l*, length of connection flange *r*, distance between mounting support *d*, toe piece *TP*, heel port *HP*, force in positive z-direction F_z, torques about x-, y-, and z-axis M_x, M_y, and M_z, respectively.

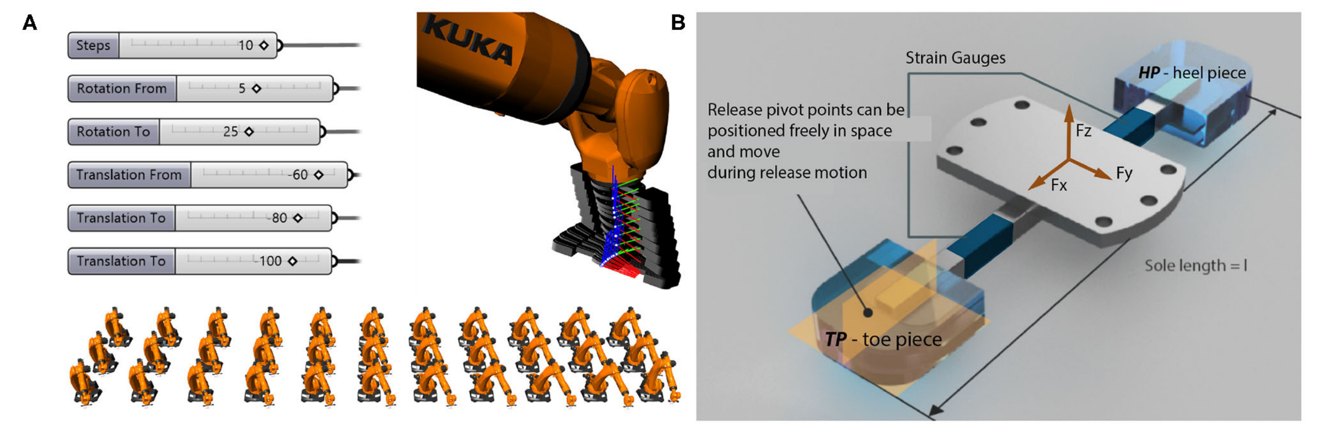

FIGURE 2 | (A) Example of robot motion sequence and software user interface: Top: Image sequence of front piece release. Bottom: Inclined back-weighted toe piece release situation. **(B)** Ski boot replacing device made up of a connection flange in the middle welded to a steel-square-pipe, which is equipped with strain gauges located in the x-y-plane and the x-z-plane both toward the front and the back portion.

bigger the load applied to the ski. $F_{z,TP} < 0\ N$, due to the mechanical properties of the ski. The length from the mounting at the back part of the ski to the heel piece was much shorter than the length from the front portion to the front mounting of the ski, which caused a kind of horizontal s-shaped deformation resulting in a negative force acting at the front portion of the ski boot replacing device.

C – boot heel moves up, with boot tip as center of rotation: The minimum value in $F_{z,HP}$ at the end of this section gave the release value of the binding heel piece. $F_{z,TP}$ increased to even higher positive values within this section, which was related to an imperfect center of rotation at the front end of the front portion close to the anti-friction device. The bigger the displacement in z-direction, the higher the maximum $F_{z,TP}$ value. However, the heel piece's release values were not influenced by alternating $F_{z,TP}$ forces.

D – boot released: In this section, the boot's heel portion was released from the binding's heel piece, resulting in a final value of $F_{z,HP} = 0\ N$, whereas the front of the boot still remained in the binding. Thus, $F_{z,TP} \neq 0\ N$, showed a final non-zero value.

3.1.2. Toe Piece Openings/Backward Lateral Release

Time signals of a test of the toe piece opening motion scheme are presented in **Figure 5** for the purpose of demonstrating the ability to identify the movement pattern by analyzing the time signals. As previously described, there is an inclination in z-direction, followed by rotation around the y-axis of 5 with the center of rotation (*COR*) located in the middle of the boot replacing device. The heel portion was even more deflected in negative z-direction, whereas the front portion moved back up a bit. The rotation around the y-axis should simulate a back-weighted falling situation. Finally, the lateral release of the binding's front piece was performed by rotating the ski boot replacing device around the z-axis with the center of rotation being placed at the heel end. A normalization of the forces and time was done for the same reasons already mentioned in the description of heel

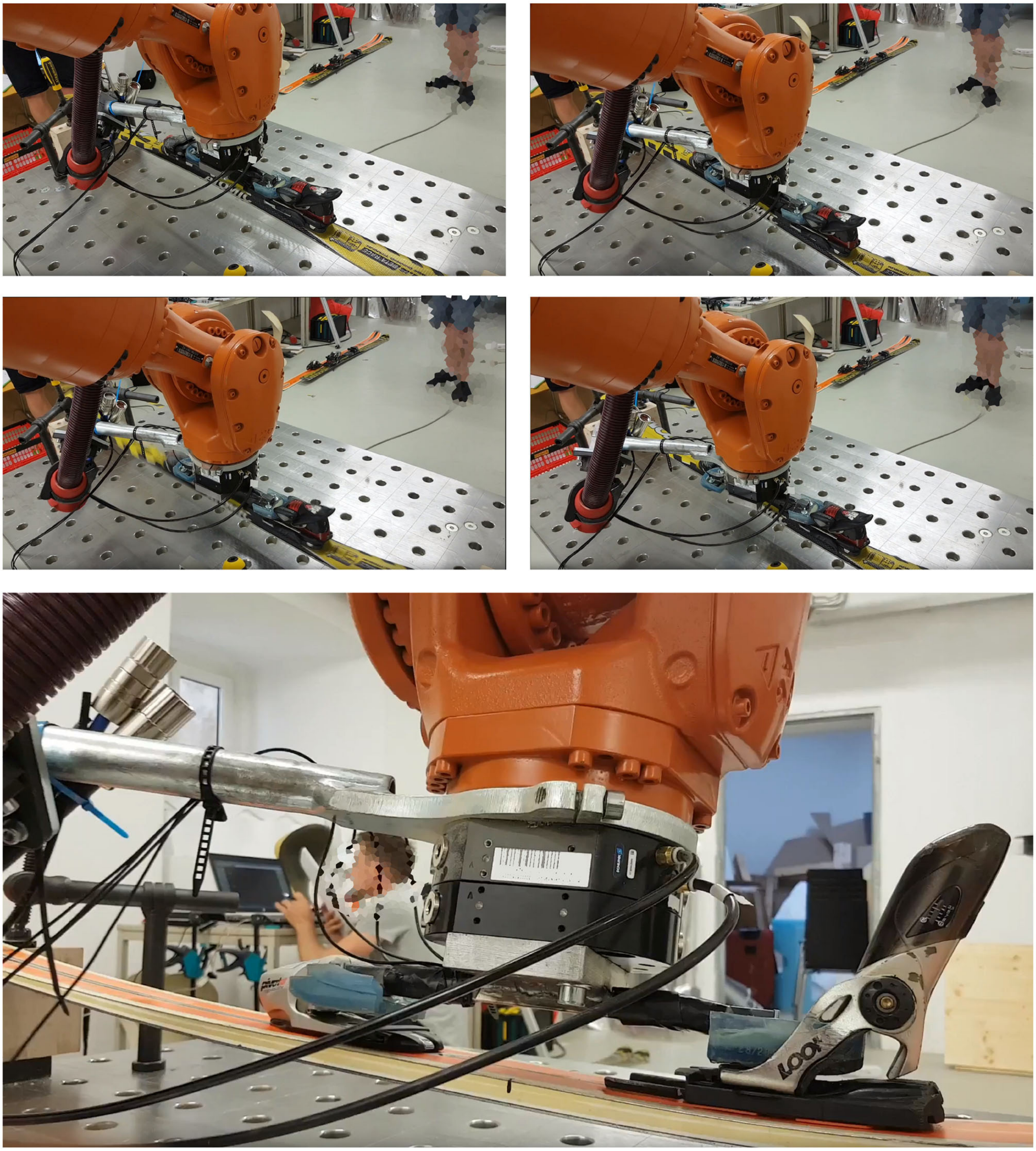

FIGURE 3 | Photo sequence of an inclined back-weighted toe piece release situation: Top left: Ski in starting position (ski rests on supports without any inclination). Top right: Ski is deflected in negative z-direction. Mid left: Rotation around the y-axis to adumbrate skier's layback. Mid right: Toe piece release. Bottom: Toe piece release from zoomed side view.

piece openings. The plot is divided into four sections to make explanations easier.

A – boot rests in binding, ski already deflected in negative z-direction: Both forces in z-direction are positive ($F_{z,TP} > 0\ N, F_{z,HP} > 0\ N$) due to deflection in negative z-direction as the bending of the ski causes strains within the ski structure, which act against the end-effector.

B – center of mass moves back: In this section, a movement of the center of mass to the back of a skier was imitated by a rotation around the y-axis resulting in a decrease of $F_{z,TP}(t_B) < 0\ N <$

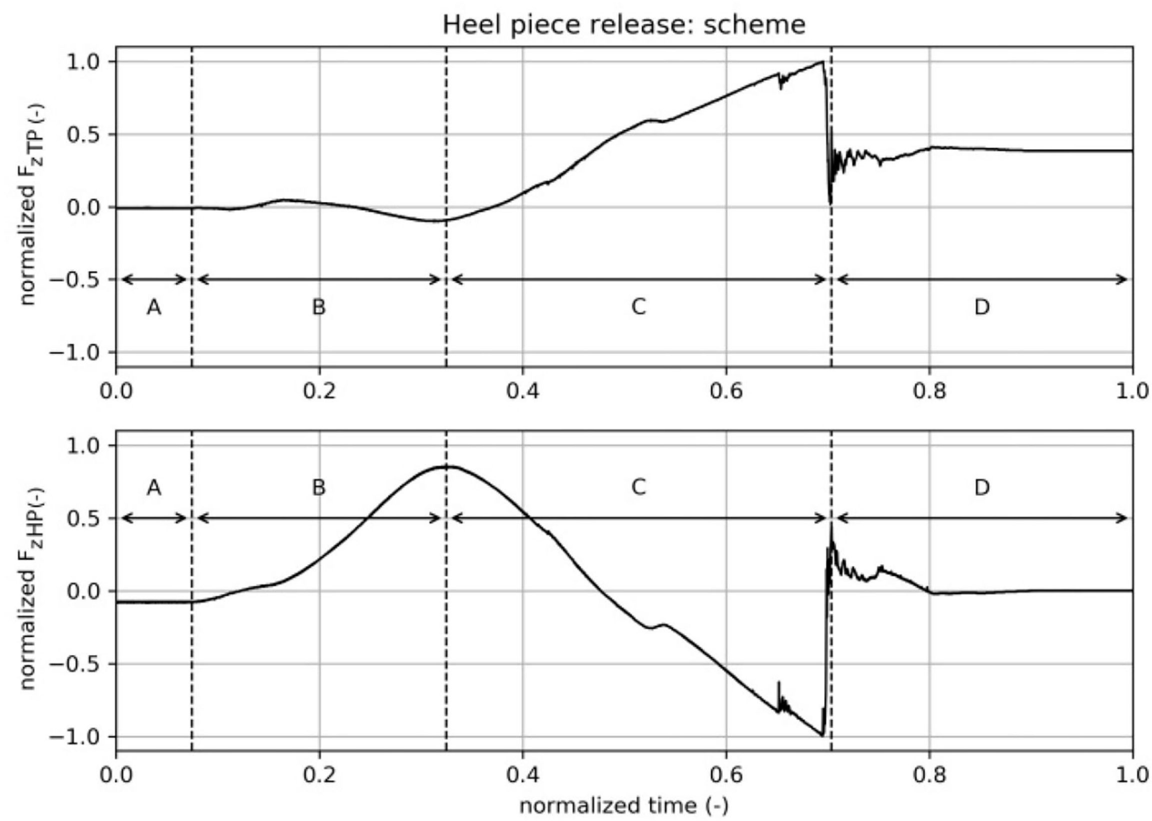

FIGURE 4 | Heel piece release motion scheme, time signals: A—boot rests in binding, B—deflection of ski, C—boot heel moves up, D—boot released.

$F_{z,TP}(t_A)$ and an increase of $F_{z,HP}(t_B) > F_{z,HP}(t_A) > 0\ N$, respectively. The center of rotation was located in the middle of the boot sole. In the scheme depicted in **Figure 5**, the robot rested in this position for a period of time before section *C* was initiated.

C – lateral movement of the boot tip, center of rotation at back of heel: Within this period, the boot performed the lateral movement of the boot's tip in order to get the corresponding release force $F_{y,TP} = F_r$, where $F_r = \min(F_{y,TP})$. The center of rotation was located in the back end of the heel and the boot rotated around the z-axis. It was observed that there was no sudden stepwise change of $F_{y,TP}$ when it exceeded the release force F_r but increased steadily to $F_{y,TP} = 0\ N$. In the first part of section *C*, the measured force $F_{y,TP}$ decreased to its minimum value and the lever arm of the ski binding's front part generated a counteracting force to the lateral movement, i.e., mainly in positive y-direction. At the position where $F_{y,TP} = F_r$, the highest part of the boot front plate's curvature was reached and the binding's lever arm induced mainly a force in negative x-direction, i.e., the binding clamped the boot from toe to heel in the y-z plane instead of the initially induced clamping of solely the toe piece in the x-z plane. Later, the boot's curvature decreased, i.e., the center line of the boot has passed the tip of the binding's lever arm, resulting in a decrease of the clamping force until the toe was fully released. The effect of clamping the boot in the y-z plane induced changes of the forces $F_{z,TP}$ and $F_{z,HP}$, especially in the latter part of section *C*.

D – boot released: The boot's toe piece was fully released. As a result, the forces $F_{y,TP} = 0\ N$ and $F_{z,TP} = 0\ N$ as the toe piece did not touch any part of the binding any longer, whereas the heel was still located in the binding's back part, thus $F_{z,HP} > 0\ N$. $F_{z,HP}(t_D) < F_{z,HP}(t_A)$ due to the decreased internal forces, i.e., stress and strain, in the ski as a consequence of the ski's change in deflection shape.

3.2. Release Forces

For the determination of the release forces, each motion pattern was repeated at least five times in order to allow a proper statistical evaluation taking a Student's *t*-test into account assuming a normal distribution of the collected data.The mean value and its corresponding 95% level of confidence was calculated and displayed in **Figure 6** as circles for the mean values and error bars representing the 95% confidence level. If the collected data of one deflection group lay outside the 95% confidence level range of another deflection group, a significant difference in the two groups can be assumed, i.e., the deformation of the ski does significantly influence the release force of the heel piece opening mechanism.

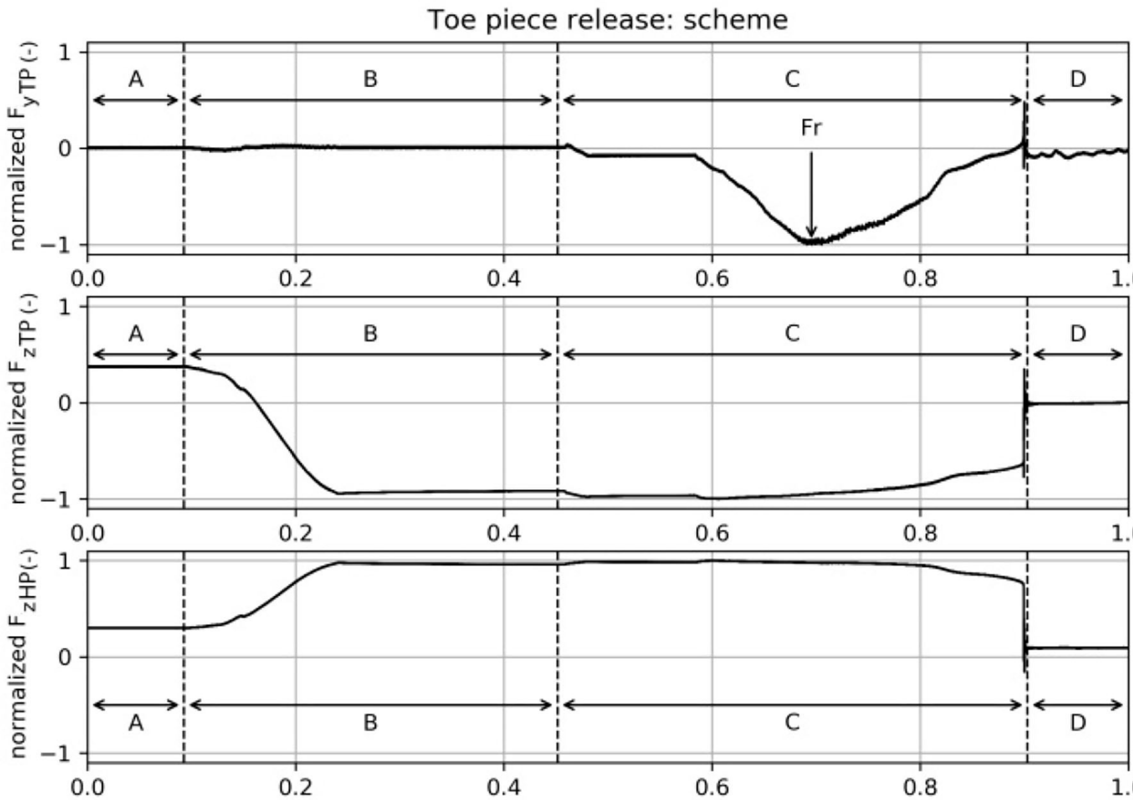

FIGURE 5 | Toe piece release motion scheme, time signals: A—boot rests in binding, B—center of mass moves backwards, C—lateral movement of the boot tip, D—boot released (F_r... release force).

3.2.1. Heel Piece Openings/Forward Bending Release

The measured release forces and confidence levels were normalized using the absolute values of the $z = -60$ mm deflection scheme (**Figure 6**, *1.c*). As the tested safety bindings were of different age and design (Atomic binding contained a robust binding plate which the Look binding did not have), the examined ski's were of different lengths, as well as the release mechanism's adjustment may not be absolutely identical, it was decided to normalize, because the authors were not interested in the quality or rating of individual brands. The $z = -60$ mm test was chosen for normalization as this deflection depth was also evaluated during all other test series. The measurement results did not show any statistically significant influence of the motion pattern concerning the heel piece release forces. Thus, a sole alternating horizontal bending of the ski did not affect the release force of the heel piece opening mechanism. However, taking a closer look at the single confidence levels, it could be seen that the additionally applied rotation of 10° around the x-axis caused a doubling in the release force's variance (**Figure 6**, *1.d*: approximately ±15%) compared to the previous tests without x-axis-rotation (**Figure 6**, *1.a* to *1.c*: approximately ±7%). The higher variance in release forces could indicate that the safety binding's release mechanism is affected by such a ski deformation, which results in a less accurate triggering of the opening apparatus.

3.2.2. Toe Piece Openings/Backward Lateral Release

The measured release forces and confidence levels were normalized using the absolute values of the $z = -60$ mm deflection scheme (**Figure 6**, *2.c*). Motion pattern *2.c* was repeated seven times but unfortunately, the first five tests turned out to be erroneous as closer inspection of the time signals revealed different behavior of these tests compared to the rest of the whole test series. A detailed analysis of the photo and video documentation confirmed that during these first five tests a systematic error in the mounting of the setup occurred. As a result, there were only two valid samples of pattern *2.c* available, which did not allow a proper statistical analysis other than evaluating its mean value. However, the whole test series showed an increase in the release forces with increasing deflection of the ski in negative z-direction. Apart from pattern *2.c*, the test results differ statistically significantly from each other. As the release forces seemed to increase linearly with increasing deflection, an extreme deformation with $z = -85$ mm was also investigated. It turned out that even such an unnatural bending of the ski still allowed for assuming a linear relationship.

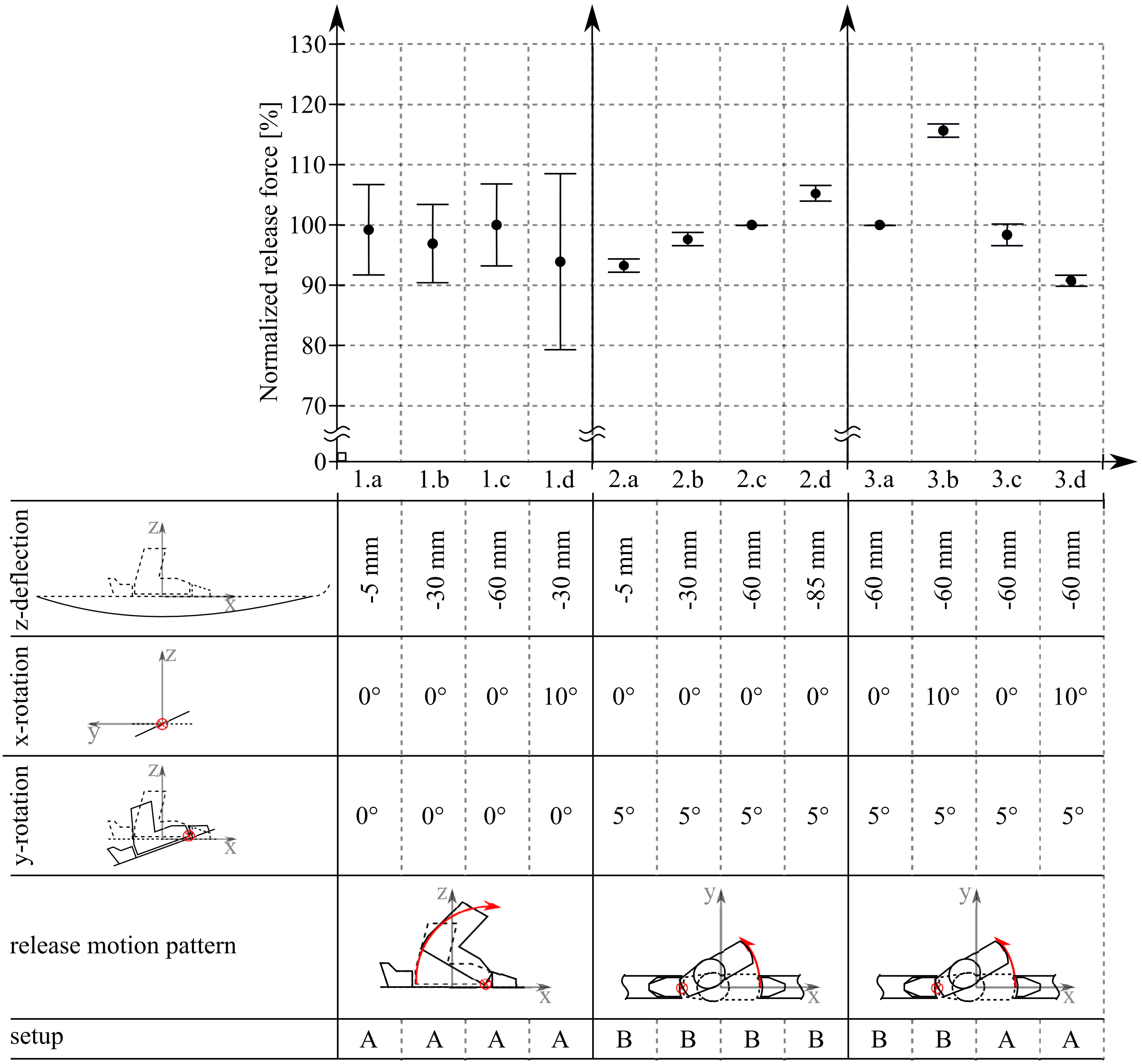

FIGURE 6 | Release forces and 95% level of confidence for different release motion patterns.

Finally, the influence of an additionally applied 10° rotation around the x-axis on the toe piece release force at a deflection of $z = -60$ mm was observed for both ski and safety binding setups. A comparison of the 0° vs. 10° x-axis rotation for ski setup *B* (Dynastar setup) and *A* (Atomic setup) is shown in **Figure 6**, *3.a* vs. *3.b* and *3.c* vs. *3.d*, respectively. All the presented values were normalized by pattern *3.a*[13]. It could be seen that the two binding setups did not differ significantly for the tests without additional x-rotation (**Figure 6**, *3.a* and *3.c*). The small deviation in their mean values could be due to slightly different adjustments of the bindings' safety mechanisms. The application of a rotation around the x-axis resulted in significantly different release forces for both ski setups. Interestingly, the rotation caused a significant force increase in setup *B*, whereas in setup *A* the release force decreased.

4. DISCUSSION

4.1. Release Situations

Heel piece release: As shown above, applied forces for heel piece release along the sagittal plane did not show any significant aberration of release forces, whereas inclining the test ski on x-axis during deflection loading lead to a greater dispersion.

[13] Release motion *3.a* equals *2.c*. *2.c* was plotted again in *3.a* for better clearness and comparison reasons.

Toe piece release: The results demonstrated that BIAD falling mechanisms should be achievable to simulate with this method in future. More elaborate binding types[14] could be tested more severely without breakage of the ski-boot-binding system, which could reveal clearer aberration in release forces in the Cartesian x-y-z directions relative to the ski inclination. This is of high interest because ACL strains correlate with the movement of the body's center of gravity and the movement of the skis connected to the snow surface. The resulting quadriceps loading produces anterior tibial translation[15] and intrinsic strain to the ACL (Demorat et al., 2004). In an inclined back-weighted toe piece release situation (**Figure 3**), constraining forces were observed by an altered distance between sole and toe piece gliding plate. Additionally, upward forces on the toe piece release levers varied greatly. In skiing, this situation could lead to delayed or no binding release resulting in injury or binding damage.

4.2. Advantages, Limits, and Constraints

The tests demonstrated that quasi-static binding testing for research purposes works precisely and release displacement can be simulated and programmed fast. Pivot points were measured manually and aligned with the robot coordinate space. Hereby, a normalized procedure to define pivots would strengthen the informative value of this method. This bench test allowed for accurate testing and prompt adjustment of movement paths. As this apparatus had a fixated ski boot sole, the synchronized movement on different spatial planes was possible. Although the robot was very accurate with a spatial displacement accuracy of ±0.06 mm and the end-effector was calibrated by means of a primary standard resulting in a relative uncertainty of ±0.5% over the total measuring range, it could not fully be guaranteed that any systematic errors occurred in the test setup. In order to further suppress systematic errors and thus increase the overall accuracy of the testing setup, an *in situ* calibration would be required. Unfortunately, such an *in situ* calibration apparatus would be rather complicated to be designed and realized.

Regarding the aforementioned experiments, execution speed of the release did not shown any significant aberration. Different acceleration patterns in loading were investigated. Key factors with reference to release forces definitely were as follows:

1. Ski bending and counter pressure.
2. Type of supports especially when executing twisted release motion.

A defined negative form to bend the ski against would additionally help to simulate boot induced back weighted fall mechanisms.

Tests with one support on either the front or the back side of the ski would result in more realistic representations of load distributions during falling schemes, i.e., during back weighted landing, respectively, BIAD situations the back part of the ski is strongly bent against the back support, whereas the front part would move freely, and vice versa for slip-catch and dynamic snow plow injury mechanisms. Nonetheless, the supports only fixated the ski sideways to avoid any support-induced ski bending. Especially for testing more extreme displacement paths, a stop signal should be implemented when an overload is measured to avoid equipment damage. This would also apply for high-dynamic testing because of its hard predictability. The developed measurement setup implemented in the ski boot replacing device showed that it was possible to ascertain the motion pattern applied to the device by interpreting the time signals. Transferring such a measurement setup to a real ski boot in combination with a mobile real-time analyzing tool could lead to the development of new safety bindings, which adjust the release mechanisms based on the motion pattern recognition. However, the method presented in this paper was only tested in the artificial surrounding of a laboratory using rather simple movements performed by an industrial robot. Furthermore, as the measurement setup applied to the end-effector was kept rather simple for the tests presented in this paper, the motion patterns performed by the robot also were kept simple. It is obvious that the presented setup cannot both be easily applied to ski boots and detect rather complex falling situations during real skiing, but it could be used as a kind of starting point for further more sophisticated developments. To develop knee-specific three-dimensional release testing paths that are more representative, in consideration of knee injuries and its counterpart, the pre-release malfunction of a ski safety binding, and motion capturing of artificial falling situations, respectively, musculoskeletal analysis computer models would enable further insight for expert evaluation.

This study was conducted to evaluate the accuracy and the constraints of this new method utilizing boot-sole-plane measurements. Basic release paths as well as twisted release movements with the focus on the backward loading of the bindings were put in the foreground of the described testing. As a result, several multiaxial release actions were calculated to compare aberrations in force loading patterns. Different release speeds did not show significant deviations in release forces over the conducted tests. Release speed was not included into further analysis here. The method allows quick changes of the displacement path triggering the release action of the binding. The high precision movement of an industrial robot and the iterative control over the movements through parametric programming are beneficial aspects of this setup. This might be of interest for the future work within following applied research topics.

5. PRACTICAL APPLICATIONS

5.1. Release and Retention Behavior Testing of Ski Bindings

Supej et al. (Supej and Senner, 2017), for instance, have shown elaborately that modern bindings, no matter if mounted directly or mounted on a binding plate, were within the generous boundaries of DIN ISO 11088. In particular, there

[14] such as diagonal release bindings, dual pivot bindings or vertical release bindings.
[15] Movement of tibia and Os femoris.

is an ongoing discussion[16] about binding settings for female skiers, who could profit from lowered release settings within the norm[17] (Laporte et al., 2009; Posch et al., 2017a,b) and failure of binding release seems to be about 20% higher for females compared to males (Ruedl et al., 2015, 2016). There is also a significant higher amount of false negatives during backward falling situations compared to forward falling (87 vs. 72%, $p = 0.002$) (Ruedl et al., 2015). But it is a tightrope walk between the reliable release of mechanical ski bindings in twisting fall situations[18] such as described in Pressman and Johnson (2003b), Bere et al. (2013), Bere et al. (2011) and the danger of pre-release malfunction (false positives). The further development of representative release paths via 3D motion tracking could help to emulate the release action of forward twisting falls and backward twisting falls with the robot.

5.2. New Product Development: Thinking Out of the Box

Beginning in the 1980s, Hull et al. (Hull and Allen, 1981, Eseltine and Hull, 1991) made first approaches on developing electromechanical ski bindings that can handle a more sophisticated differentiation, which triggers the binding release action (see Gulick and Mote, 2001). Especially research groups around Senner (Senner et al., 2013; Senner et al., 2014; Nusser et al., 2016) regularly brought electromechanical approaches into discussion on the search for a way to reduce knee injuries. Recent mechanical binding models address knee injuries by adding degrees of freedom to the toe piece. Ahlbäumer et al. (1999) investigated the possibilities and the restrictions of toe-bindings with multi-directional release while applying backward fall related forces using testing devices for ski bindings according to ISO 9462 IAS 100. Concerning this matter, it is still unclear how vertical release forces should correlate with the lateral release settings of the toe piece and how false positives could be avoided. Similarly, some bindings[19] offer a lateral release option in the heel piece of the binding.

This method can be useful in future to test new electronical or mechanical release features more distinctively. It can also be used for stress analysis of new components or the analysis of material behavior (Knye et al., 2016).

In developing new skis, S-B-B[20] combinations, the detailed knowledge of bending profiles and ski behavior is key information. This method can easily be applied for those demands and even simulate the dynamic loading of the S-B-B system. The robots' limits in acceleration speed and deceleration speed while applying critical forces to the S-B-B system allow high dynamic testing[21] of modern S-B-B setups. For example, by integrating the shake behavior of skiing at high speeds as a test parameter. Nonetheless, the testing of new binding developments in view of slow speed falls seems to be of great importance, because of the relation between release speeds and the timing of muscle contractions (Aune et al., 1995). The applied force loads and vibration of the robot could be aligned with empiric on-piste data from other studies (Gilgien et al., 2013, 2015; Fasel et al., 2016; Spörri et al., 2017). The addition of resilient negative bending profiles (ski slope surface) to the setup will also enable the integration of ground reaction forces and should be considered for further development (Müller, 1994; Babiel et al., 1997; Nakazato et al., 2011). Furthermore, the integration of inverse kinematics in the programming would allow the calculation of position and rotation data of a virtual knee.

The plausibility to integrate an artificial lower leg and knee in the system needs to be assessed by bio-mechanical experts. Knee surrogates, for example, have been used to evaluate knee braces used especially in contact sports[22] (Cawley et al., 1989; Brown et al., 1990) and lately the evaluation of knee braces and ski safety bindings in alpine skiing (Nusser et al., 2016).

Furthermore, in the production lines of high-quality ski models, manual testing and bending of skis is an important part of the final fine tuning. To that effect, this method has to be tested and developed further to gain more insight into how those processes could be assisted or replaced.

6. OUTLOOK

While there are plenty of solutions to mechanically release a binding in multiple directions, the authors assume it could be revealing, if force loading patterns can be diagnosed somewhere in the skiing equipment, that can be directly related to knee injury related falls. This means only specific overloading leads to an early release of an "intelligent" ski binding. We assume the integration of a sensor-equipped ski boot (Nimmervoll et al., 2020) as well as the integration of sensors that are positioned in the ski bindings' interfaces (Nakazato et al., 2011; Martínez Álvarez et al., 2020) as promising options for future testing. Force data from the slopes can be integrated in data analysis that allows more detailed studies of interrelations between binding forces and

[16] In a case–control study in Flaine (Laporte et al., 2009), they asserted that 15% lower set binding release values in female skiers than the settings recommended by the ISO 11088 standard would significantly reduce knee injuries.

[17] The are rigorous differences between female and male skiers concerning the knee injury rates (Greenwald and Toelcke, 1997; Donner and Walther, 2007; Ruedl et al., 2009; Ekeland and Hospital, 2016).

[18] Ruedl et al. (2009) assume that the shorter carving skis compared to the longer and straight-shaped traditional skis cause a distribution change of the ACL injury mechanisms from backward twisting fall (29%) to forward twisting fall (51%) among female skiers.

[19] e.g., Kneebinding of Kneebinding, Inc. http://www.kneebinding.com/ The exact effect to knee injury prevention and binding pre-release occurrence seems still unclear (Senner et al., 2014) or Kingpin bindings of Marker GmbH https://www.marker.net/en/products/bindings/touring/kingpin-13/

[20] Ski Binding Boot.

[21] Angular velocities of the six axis vary between 115°/s and 260°/s at 150 kg nominal load capacity.

[22] As the knee itself is a complex structure of a synovial joint and viscoelastic ligaments, of course, the effects of braces and knee proprioception offer a wide field for discussion (Teitz et al., 1987; Requa and Garrick, 1990).

measured forces in the ski boot. To gain more insight into the assumption that occurring forces can be reliably differentiated between, one could say, sportive skiing load patterns and ACL endangering load patterns, the authors searched for versatile method to measure forces in laboratory conditions. Referring to this, this experiment is a promising endeavor to correlate prospective real-world data with robot simulation data in future studies.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and the design.

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BRIEF RESEARCH REPORT
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Is Hemoglobin Mass at Age 16 a Predictor for National Team Membership at Age 25 in Cross-Country Skiers and Triathletes?

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We recently measured the development of hemoglobin mass (Hb_{mass}) in 10 Swiss national team endurance athletes between ages 16–19. Level of Hb_{mass} at age 16 was an important predictor for Hb_{mass} and endurance performance at age 19. The aim was to determine how many of these young athletes were still members of Swiss national teams (NT) at age 25, how many already terminated their career (TC), and whether Hb_{mass} at ages 16 and 19 was different between the NT and TC group. We measured Hb_{mass} using the optimized carbon monoxide re-breathing technique in 10 high-performing endurance athletes every 0.5 years beginning at age 16 and ending at age 19. At age 25, two athletes were in the NT group and eight athletes in the TC group. Mean absolute, body weight-, and lean body mass (LBM) related Hb_{mass} at age 16 was 833 ± 61 g, 13.7 ± 0.2 g/kg and 14.2 ± 0.2 g/kg LBM in the NT group and 742 ± 83 g, 12.2 ± 0.7 g/kg and 12.8 ± 0.8 g/kg LBM in the TC group. At age 19, Hb_{mass} was 1,042 ± 89 g, 14.6 ± 0.2 g/kg and 15.4 ± 0.2 g/kg LBM in the NT group and 863 ± 109 g, 12.7 ± 1.1 g/kg and 13.5 ± 1.1 g/kg LBM in the TC group. Body weight- and LBM related Hb_{mass} were higher in the NT group than in the TC group at ages 16 and 19 ($p < 0.05$). These results indicate, that Hb_{mass} at ages 16 and 19 possibly could be an important predictor for later national team membership in endurance disciplines.

Keywords: blood volume, CO-rebreathing, talent identification, adolescents, maturation

INTRODUCTION

It is well-documented that elite endurance athletes are characterized by having up to 40% higher levels of total hemoglobin mass (Hb_{mass}) than untrained subjects (Kjellberg et al., 1949). Hb_{mass} strongly correlates with maximal oxygen uptake in endurance national team athletes (Schmidt and Prommer, 2008), and there is a strong correlation between Hb_{mass} and endurance performance, even in groups of highly-trained endurance athletes (Hauser et al., 2018; Zelenkova et al., 2019b). Several studies (Wehrlin and Marti, 2006; Wehrlin et al., 2006; Hauser et al., 2016, 2017) have demonstrated that Hb_{mass} in elite athletes increases temporarily with altitude training, but the variation of Hb_{mass} over a training season is minimal (Garvican et al., 2010). In addition, long-term endurance training (without altitude training) in elite athletes does not increase Hb_{mass} (Wehrlin et al., 2016) and Hb_{mass} in elite endurance athletes remains constant over many years (Wehrlin et al., 2016). Therefore, the high Hb_{mass} of elite athletes is more likely to originate from a specific genetic predisposition than from endurance training (Bouchard et al., 1999; Steiner et al., 2019). We previously hypothesized that we could measure Hb_{mass} in endurance athletes at age 16 to identify talent for endurance disciplines. In the first study (Steiner and Wehrlin, 2011), we compared cross-sectional data of Hb_{mass} in cross-country skiers and triathletes at age 16 with Hb_{mass} in national team athletes at ages 19 and 28 elite national team athletes. While the Hb_{mass} measurements at ages 19 and 28 were similarly high, at age 16, athletes had 30% lower values, which did not differ from their age-matched untrained controls (Steiner and Wehrlin, 2011). Therefore, we hypothesized that Hb_{mass} increases with endurance training in adolescents between ages 16 and 19 (Steiner and Wehrlin, 2011). In a follow-up longitudinal study, we continued our Hb_{mass} measurements at age 16 athletes and controls for an additional 3 years (Steiner et al., 2019). Contrary to our hypothesis, there was no difference in the level of body weight related Hb_{mass} between athletes and those in the control group at ages 16 and 19. Furthermore, Hb_{mass} increased to the same extent in the endurance athlete group as in the untrained control group, and there was no correlation between the amount of endurance training and the increase in Hb_{mass} (Steiner et al., 2019). Interestingly, there was a wide range in the Hb_{mass} level at ages 16 and 19, and the level of Hb_{mass} at age 16 was an important predictor for Hb_{mass} and performance at age 19 (Steiner et al., 2019).

However, at age 19, it was not clear which of the athletes were going to be successful in transition to the national team and if a high Hb_{mass} was a possible prerequisite. The aim of this brief report was to analyze how many athletes between ages 16–19 were still members of the Swiss national team at age 25, how many terminated their career, and if Hb_{mass} at ages 16 and 19 was different between these two groups.

METHODS

Study Design

Six years after the last Hb_{mass} measurement of the athletes at age 19 (Steiner et al., 2019) when the endurance athletes were at age 25, we analyzed which of the 10 cross-country skiers and triathletes were members of the Swiss national team (NT group) and which athletes had terminated their career (TC group). We then retrospectively compared the Hb_{mass} of both groups at ages 16 and 19.

Subjects

Ten male adolescent endurance athletes (five cross-country skiers and five triathletes) participated in the study. Since no junior national teams exist at age 16 cross-country skiers or triathletes, the inclusion criterion for athletes was a national top 15 overall ranking in either cross-country skiing or triathlon in the season preceding the study period. There was no difference in anthropometric data between the NT and the TC groups.

Ethics Statement

The study was approved by the Regional Ethic Committee in Berne, Switzerland, and was carried out according to the recommendations of the Helsinki Declaration. All subjects and parents gave their written consent prior to any testing.

Determination of Hb_{mass}

The method is described in detail in the original paper (Steiner et al., 2019). In summary, the athletes and controls inhaled a bolus of pure CO (CO-doses were determined to be 1.2 mL·kg^{-1}). Before inhalation, as well as 6 and 8 min after inhalation, capillary blood samples (35 μL) were taken from the participants' earlobe and analyzed for percent carboxyhemoglobin (HbCO) using a diode array spectrophotometer (ABL 800flex, Radiometer A/S, Copenhagen, Denmark). All CO-rebreathing procedures were conducted by the same experienced investigator to avoid inter-tester variability. Our laboratory observed a typical error between 1.1 and 1.4% from duplicate measurements of Hb_{mass} through the described method (Naef et al., 2015).

Data Analysis

Hb_{mass}, anthropometric and training characteristics of the NT and TC groups were presented as the mean ± standard deviation (SD). After passing a normality test (Shapiro-Wilk) and an equal variance test (Brown-Forsyth), differences in Hb_{mass} between the NT and TC groups at ages 16 and 19 were calculated with the Student's *t*-test. Effect sizes were calculated after Cohen (Cohen, 1988).

RESULTS

At age 25, two athletes were members of the national team (NT group) and eight athletes had terminated their career (TC group). Mean absolute, body weight-, and lean body mass (LBM) related Hb_{mass} at age 16 were 833 ± 61 g, 13.7 ± 0.2 g/kg and 14.2 ± 0.2 g/kg LBM in the NT group and 742 ± 83 g, 12.2 ± 0.7 g/kg and 12.8 ± 0.8 g/kg LBM in the TC group. At age 19, Hb_{mass} was 1,042 ± 89 g, 14.6 ± 0.2 g/kg and 15.4 ± 0.2 g/kg LBM in the NT group and 863 ± 109 g,12.7 ± 1.1 g/kg and 13.5 ± 1.1 in the TC group. Body weight- and lean body mass related Hb_{mass} were higher in the NT group than in the TC group at both ages 16 and 19 ($p < 0.05$) and the difference of the groups showed a large effect size (> 0.8). **Figure 1** shows individual data of all athletes as well as the mean ± SD of the NT and TC groups at and between ages 16 and 19. **Table 1** shows anthropometric and training characteristics of both group. There was no difference between groups.

DISCUSSION AND CONCLUSION

The main finding of this brief research report is that the mean body weight related Hb_{mass} in the NT group at age 16 was remarkably 1.5 g/kg higher than that in the TC group (1.9 g/kg higher at age 19; **Figure 1**). Furthermore, body weight related Hb_{mass} values of the NT group reached 13.7 g/kg at age 16 and 14.6 g/kg at age 19. These measurements were very similar to those observed in previous investigations with juniors at age 19 (14.2 g/kg) and national team athletes at age 28 (14.6 g/kg)

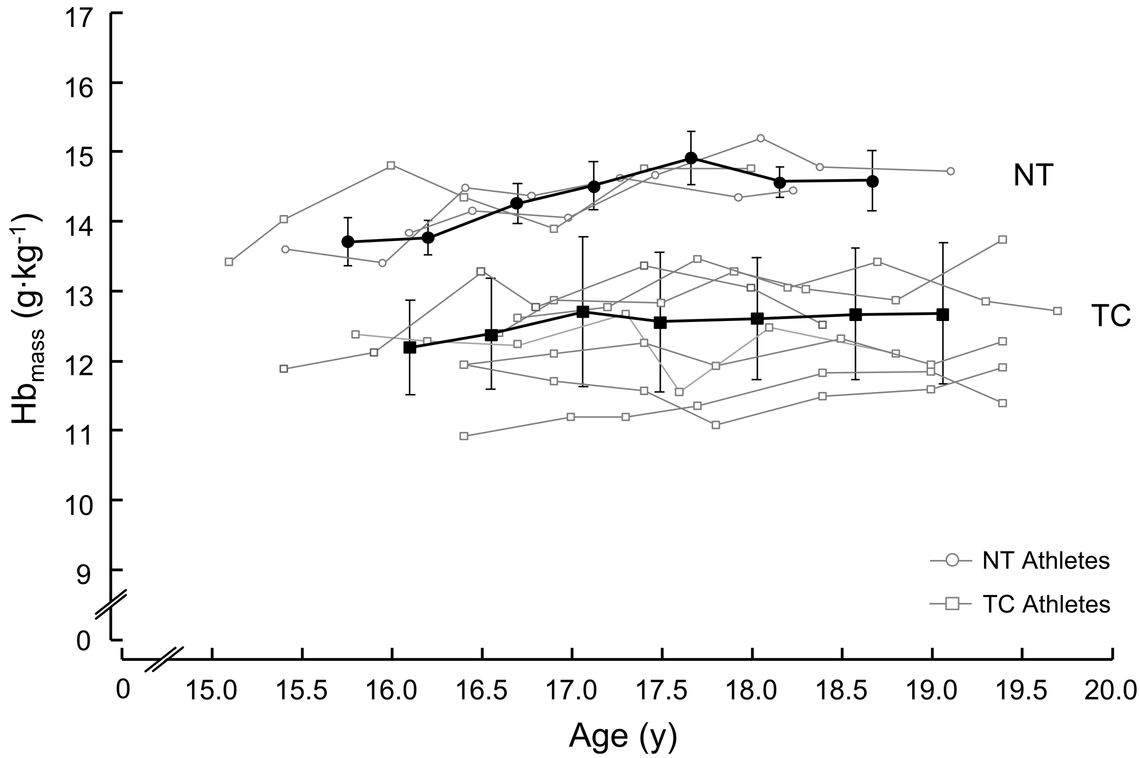

FIGURE 1 | Development of body weight related hemoglobin mass (Hb_{mass}) in the national team (NT) group and the terminated career (TC) group during adolescence (ages 16 to 19).

TABLE 1 | Characteristics of the NT ($n = 2$) and TC ($n = 8$) group at age 16 and 19 years.

Group	Age (years)	Body mass (kg)	Height (cm)	LBM (kg)	VO_2max (mL · min^{-1})	VO_2max (mL · min^{-1} · kg^{-1})	VO_2max (mL · min^{-1} · kg^{-1} LBM)	Endurance training (hours)	Total training (hours)
NT	15.8 ± 0.5	60.8 ± 5.2	178 ± 6	58.6 ± 4.9	4202 ± 108	69.3 ± 4.1	71.8 ± 4.1	7.0 ± 2.8	8.5 ± 3.5
TC	16.1 ± 0.6	60.9 ± 5.8	176 ± 5	57.8 ± 5.0	4037 ± 416	66.3 ± 3.1	69.9 ± 3.6	8.1 ± 1.4	8.7 ± 1.5
NT	18.7 ± 0.6	71.5 ± 7.1	181 ± 7	67.9 ± 6.7	5301 ± 634	74.1 ± 1.6	77.9 ± 1.6	8.2 ± 1.8	9.7 ± 2.3
TC	19.1 ± 0.6	68.0 ± 6.0	180 ± 6	63.9 ± 5.2	4735 ± 378	69.8 ± 4.1	74.2 ± 3.8	8.0 ± 2.3	8.7 ± 2.2

NT, National team membership at age 25; TC, Terminated career at age 25; LBM, Lean body mass; Values as mean ± SD.

cross-country skiers and triathletes (Steiner and Wehrlin, 2011). Even though, on average, body weight-related Hb_{mass} increased by ∼0.3 g/kg per year between ages 16 and 19, for future elite national team athletes, Hb_{mass} levels of 13.5–14 g/kg at age 16 seem to be a prerequisite to transition to national team at age 25.

We think that a Hb_{mass} level of 14–15 g/kg at age 28 is needed to be a member of a national team in endurance disciplines (Steiner and Wehrlin, 2011). This finding is supported by the fact that Hb_{mass} values from other countries elite male cross-country skiing and triathlon national teams, as well as athletes from other endurance sports, are reported to be about 14–15 g/kg (Heinicke et al., 2001; Wehrlin and Marti, 2006; Gore et al., 2013; Zelenkova et al., 2019a). Mean body weight related Hb_{mass} at age 16 was lower in the NT and TC compared to the Hb_{mass} at ages 19 and 28 (Steiner et al., 2019), which seems to be due to the fact that only two to three athletes per year have the potential to make it to the national team in cross-country skiing and triathlon. Whereas the athletes at ages 19 and 28 (Steiner et al., 2019) consisted of several age cohorts, our athletes at age 16 (NT and TC) consisted of only a 1 year cohort. This means that this group was comprised of physiologically less-talented athletes, which lowered the mean body weight related Hb_{mass}.

However, it is important to note that a high body weight related Hb_{mass} is not the only factor related to national team membership at an adult age. While the level of body weight related Hb_{mass} seems to be likely a prerequisite, it is not a guarantee for later national team membership. Other important factors like a high VO_{2max} (and every aspect of oxygen transport), the ability to utilize a high fraction of VO_{2max}, a high energy availability, a high anaerobic power, a high efficiency, a high speed capacity and strength in connection with movement specific exercise, play an important role as well (Sandbakk and Holmberg, 2017). It also needs to be emphasized, that this short report suffer from several limitations: The first point is, that we have a very low n ($n = 2$) in the NT group. Results could therefore have been biased by false positive or negative results and other confounding factors. It is also important to mention, that there could be potential differences in the physiological demands between triathlon and cross-country skiers athletes. However, our longitudinal study (Steiner et al., 2019) suggested, that Hb_{mass} at age 16 is an important predictor for Hb_{mass} at age 19. With this additional analysis of national team membership at age 25, we now can further suggest, that a high Hb_{mass} (13.5–14 g/kg) at age 16 could be an important prerequisite for future national team membership at age 28 in endurance disciplines. However, further multi–centric longitudinal studies (merging data from different national training centers) would provide larger sample size for such interesting retrospective talent identification analysis/modeling.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

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

AUTHOR CONTRIBUTIONS

JW and TS designed the study, performed the data handling, the interpretation of the data, and the statistical analyses. TS collected the data, contributed to the writing of the manuscript, and designed the figure. JW drafted the manuscript. All authors contributed to the article and approved the submitted version.

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Studying Force Patterns in an Alpine Ski Boot and Their Relation to Riding Styles and Falling Mechanisms

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In skiing, performance and safety can depend on small details. Consequently, the measurement of forces within the ski boots, which represent the essential form-fitting and force transmitting interface during skiing, will lead to enhanced performance and more importantly safety. This study presents a methodology to measure force patterns (continuous data acquisition) under laboratory as well as realistic slope conditions. The force measurements will be analyzed to gain insights of the skiing style, skiing technique, specific falling mechanisms (i.e., boot induced anterior drawer, phantom foot, hyperextension of the knee joint, and valgus-external rotation). Furthermore, the locations of force sensors in a *overlap* designed ski boot are discussed in terms of practicability and applicability. These insights are of particular interest to derive release conditions for predictive binding systems and furthermore provide data to improve the style of skiing (e.g., turn release action or center of gravity behavior). For that purpose, a ski boot was instrumented with seven force (piezoresistive) sensors while the basic structure of the boot and the binding remained unchanged. Three sensors were placed on the insole to measure ground reaction forces as well as the contact forces between the skier's foot and the boot. The other four sensors were positioned at spoiler/shaft and toecap (front sole) regions of the ski boot. The locations of the force sensors within the ski-boot are defined with regard to the main body movement while skiing (body-related planes). In addition, a commercially available ski and body mount measuring system were utilized to correlate speed, inclination and body position with the force patterns occurring during skiing on the slope as well as simulating specific body positions on an inclined ramp under laboratory conditions. The measured force revealed that the toecap (upper) sensors provide insufficient even non-conclusive data to deduce significant patterns. However, the insole sensors (heel and front sole area) as well as the spoiler/shaft (back) sensors are more reliable and show characteristic patterns indicating forward or backward lean. These results will have an important impact to the development of predictiveelectro-mechanical bindings to prevent knee-related injuries, which, from a statistical point of view, concerns largely women and young athletes.

Keywords: force patterns during skiing, skiing falling mechanisms, in lab and on the slope ski boot experiments, piezoresistive sensors, biomechanics

1. INTRODUCTION

The development of smart wearable electronics in the sports (Brunauer et al., 2020; Sperlich et al., 2020) and rehabilitation industry (Pędrys et al., 2020) leads the way to new market niches and even more it helps platform oriented business models to establish in conservative sports markets[1]. In recreational alpine skiing there are a number of wearables available (e.g., smartwatches, compact sensor units, smart insoles) to track and measure individual skiing performances as speed, stance, acceleration or vertical feet per ride. The miniaturization of sensing hardware, coupled with general acceptance of the smartphone as practical and ubiquitous control interface, makes a fast growing industry sector. Contrary to the fast development in wearable smart technologies, ski bindings remained mostly unchanged in their basic functional mechanics since the 1970s when safety release functions (side-wards release of the toe piece and upwards release of the heel unit; PTFE gliding plates) (Masia, 2018) have been introduced, which led to a decline in injury rates and a distribution shift from ankle and tibia fractures toward knee-related injuries (Kuriyama et al., 1980; Ettlinger et al., 1995; Johnson et al., 1997). The introduction of carving skis did not bring significant changes of knee injuries compared to other body parts (Burtscher et al., 2008). Ski safety bindings have not mitigated the high knee-related injury rates in a significant manner yet (Natri et al., 1999; Senner et al., 2014; Schulz, 2016), especially concerning female skiers (Kelsall and Finch, 1996; Burtscher et al., 2008; Ruedl, 2011; Sabeti, 2013; Brucker et al., 2014; Ruedl et al., 2014; Shea et al., 2014; Schulz, 2016). In 2003, 56% of injuries were located on the knee for women (Ruedl et al., 2009). The gender dependent hamstring to quadriceps ratio (HQ) is related to the tendency (susceptibility) to knee injury and is higher, the lower HQ is (Greenwald and Toelcke, 1997; EL Ashker et al., 2017). Lower Z values of the binding's release mechanism (i.e., determining the limiting torque), as recommended by the DIN-ISO 11088, may lead to lower injuries (Posch et al., 2017), however, that reasoning is controversial and neither applies to every skier nor riding style (e.g., aggressive riding, carving style, terrain, etc.). Also in youth and elite sports, severe knee injuries are common reasons for long term interruptions or discontinuations of athletic careers (Flørenes et al., 2009; Westin et al., 2012; Hildebrandt et al., 2017; Steidl-Müller et al., 2017). Especially, Koehle et al. (2002) addressed the ski binding design as one of the main preventative factors in alpine skiing. Within those knee-related falling and subsequent injury mechanisms concerning the human knee structure the *valgus-external rotation mechanism (VER)* as well as the *phantom foot mechanism* are the most common causes of structural overload (Ettlinger et al., 1995). Interestingly, Ruedl et al. (2009) stated a distribution change of anterior cruciate ligament (ACL) injury mechanisms from backward twisting fall (29%) toward forward twisting fall (51%)[2] of female carving skiers. The related non-release (false negatives) of the ski bindings occurs 2.6 times more frequently than with males (Ruedl et al., 2011). Nonetheless, frequent binding release failure in backward twisting fall situations is still a well-known challenge in the development of new ski binding with improved safety capabilities (Ahlbäumer et al., 1999; St-Onge et al., 2004; Ruedl et al., 2009; Bere et al., 2011).

Research on the skier's body position, muscular stress and ground reaction forces (GRF) (Müller, 1994; Aune et al., 1995; Färber et al., 2018; Seifert et al., 2020) as well as studies on the influence of the boot's geometry (Benoit et al., 2005) and material properties (Petrone et al., 2013) can support product development, injury prevention and the development of skiing technique. Hereby, the utilization of pressure insoles is part of present day methods to measure forces within a ski boot or generally in orthopedics (Babiel et al., 1997; Stricker et al., 2010; Nakazato et al., 2011; Adelsberger, 2014). However, only GRF of the sole can be derived/measured with these pressure insoles.

Force distribution between the inner layer and the outer shell of a modern ski boot will provide insights about bio-mechanics, skiing technique as well as force patterns occurring during athletic skiing and in critical falling situations. Consequently, a measurement system with minimal effect and disturbance to both the ski boots' structure and the standing position of the skier was developed, DAQ programmed and built. In the research of Nakazato et al. (2011), Kistler force plates (three piezoelectric sensors) where mounted below the heel piece and the toe piece of an Atomic Race 1018 binding (Atomic Austria GmbH, Altenmarkt im Pongau, Austria). Force plates lead to a higher standing position and add a total weight of 4 kg on the skis by the amplifiers, controllers, and battery packs. Additionally, Nakazato et al. (2011) used a Pedar (Novel, Munich, Germany) pressure insole (PI) instead of the regular insole. It was suggested to use force plates only when 3D force data and torques are needed. For high dynamic situations, such as powder skiing or skiing moguls, Nakazato et al. (2011) concluded that PI measurements are preferable. Stricker et al. (2010) consider PI measurements, which represent 1D pressure forces, inaccurate for most bio-mechanical analyses in skiing and snowboarding, despite the high similarity to time-dependent force characteristics of skiing. After all, the reaction force is dependent on the material's mechanical behavior (constitutive behavior) and the geometry (structure) itself. Martínez et al. (2020) showed that interchangeability of sensor technology is not given.

Consequently, the hypothesis arises that all force measuring systems for athletes' locomotion are based on the foot sole only. We withdraw this hypothesis with our applied research efforts by selecting, characterizing mechanically as well as environmentally and programming flexible (piezoresistive) force sensors. Our findings are the first attempt to incorporate these types of sensors in ski boots with very promising outcomes. With this measurement system, the most important locations within the boot for force measurement (and monitoring) can be derived in order to correlate skiers' body position with ski boot forces. Most endeavors on developing electro-mechanical binding solutions have their origin in the search for a more reliable release in conjunction with knee injuries (Hull and Allen, 1981; Eseltine and Hull, 1991; Hull et al., 1997; Gulick and Mote, 2000; Senner et al., 2013). Even mechanically advanced binding solutions with

[1]For example, software platforms like *Strava* or *Zwift* in the endurance sports sector.

[2]cf. https://www.academia.edu/7865995/Mechanism_of_ACL_Injury_in_Skiers_Letter_to_the_Editor.

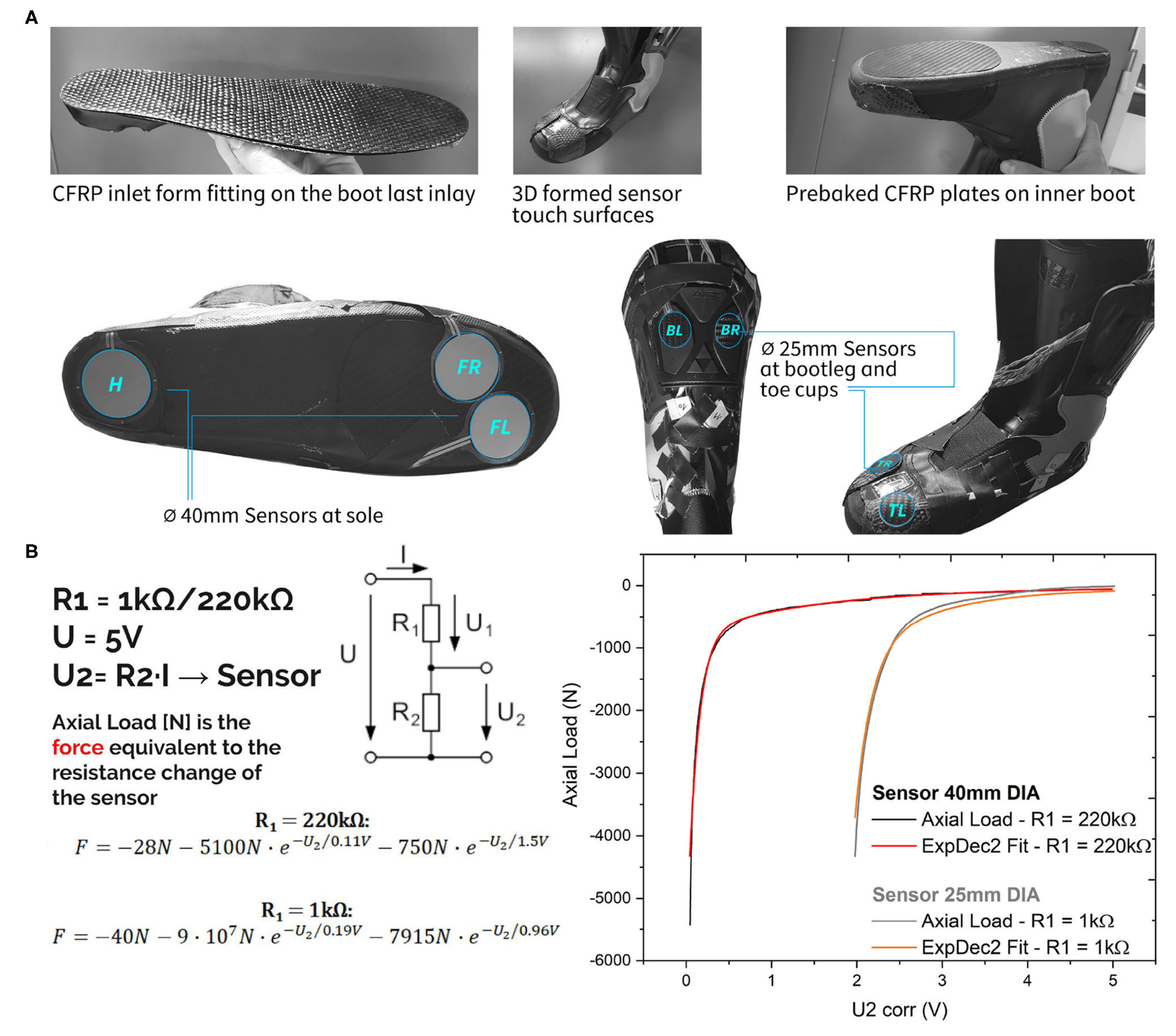

FIGURE 1 | (A) Sensor positioning and carbon fiber reinforced polymer plates to improve force transmission. **(B)** Sensor calibration scheme.

multi-directional toe units can lead to dangerous accidental release and unintended operation (Ahlbäumer et al., 1999).

The objective of this study is to gain deeper insights into GRF (on the insole) in relation to forces within the ski boot itself to recognize specific force patterns. Therefore, we examine the duration and intensity of specific positions and movements under laboratory conditions as well as on the ski slope.

2. MATERIALS AND METHODS

Considering the discussed researches and findings (see section 1), we identified a lack of measurement systems for descriptive analysis of boot-foot interactions occurring during skiing, respectively, in falling situations. Low interference of the measurement system on the confined foot within the boot (i.e., contact, interface and friction under thermal as well as mechanical loading) is required and is of tremendous importance. The sensor positions were chosen with respect to the skier movement and keeping in mind future tests with sensors integrated in injection molded plastic boots (tooling of the cavity has to be considered).

2.1. Ski Boot Instrumentation and Setup

A **right** Fischer ski boot (RC4 Curv Size 28.5 (Flex 130), Fischer Sports GmbH, Ried im Innkreis, Austria) has been modified to measure forces at seven locations within the boot. Two piezoresistive *Tactilus Sensors* (Sensor Products INC., NJ, USA) with a circular surface of 12.56 cm^2 and 0.25 mm thickness have been put to a tailored carbon sole inlay. For better force transmission form-fitting carbon fiber laminated plates have also been fixed on the inner boot. Four round sensors with a surface area of 4.9 cm^2 have additionally been placed at the ski boot's cuff and above the toes region as shown in **Figure 1A**. The positioning of these sensors was especially intended to measure force patterns of balanced skiing movements but also skiing when leaning forwards and backwards. Skis used for testing were Atomic Vantage 90 TI [2018/19 model, Allmountain Rocker, length = 184 cm, radius = 19.5 m, side cut = (129/90/119.5) mm].

2.1.1. Sensor Type and Calibration

To achieve a light and mobile data acquisition (DAQ) setup the authors utilized a micro controller Arduino (MEGA 2560) assembled with two *ADS1115 ADC 4 Channel 16Bit I2C* analog to digital converters (see **Figure 2B**). Seven sensors were wired to the Arduino unit which is carried in the backpack. The sampling frequency of the system was at 100 Hz.

A mechanical test system MTS 852 Damper Test System (MTS, Minneapolis, MN, USA) was utilized to aggregate data for the calibration curves. Therefore, a 25 kN load cell has been used for the calibration in a compression loading configuration. The sensor has been put between two elastomeric foam sheets to ensure a soft contact of the metallic compression plate fixtures and hence a better force control during loading. The sensor was wired to a serial circuit including resistances of 1 and 220 kΩ. The applied total voltage U has been 5 V. The change of the sensor voltage U2 (see **Figure 1B**) has been recorded with the DAQ system of MTS while loading up to 5 kN. The resulting characteristic of the force F(U2) has been curve fitted by an exponential decay function as shown in **Figure 1B**. This calibration function has been implemented in the Arduino code to record the force values for the seven sensors during labor as well as field tests on the piste. **Figure 2** shows the setup with the data capturing unit (580 g) placed in a backpack.

2.2. Testing the Boot-Sensor Setup Under Laboratory Conditions

An 22.5°inclined mobile ramp was covered by an expanded polypropylene foam (EPP 60 g/l) board. The foam board helped to gain edge grip. Hysteresis, respectively compression, felt natural even when applying high pulling forces up to 400 N at 22.5°slope angle (as illustrated in **Figure 3B**). As the foam structure received almost no structural damage, high reproducibility was given and the EPP gave a softer snow-like feeling to the participant. To obtain enough lateral force a rope attached to a 32 kg dead-weight at hip-level height was utilized, perpendicular to the ski direction. Resulting in pulling forces of 336 ± 14 N recorded with an electronic scale during the ramp testing procedure (ramp weight transfer).

2.2.1. General Testing Sequence

The aforementioned calibration procedure started prior to every test including the flat land and ramp weight transfer tests followed by the sequences listed in **Table 1**. The injury-related body positions (IRBP) were simulated by getting into the specific position and altering the loading to see whether significant force peaks and/or patterns can be observed or not.

Testing sequence Participants were informed of the potential risks and benefits of participation in this study prior to consenting to participate. This study was approved by the Ethics-Committee of the Federal State Upper Austria. Before starting the initial tests the participant (m = 90 kg; L = 189 cm) performed a 5 min warm-up including active movement and stretching of hamstrings and engaging hip mobility. Each test sequence started level ground where the system was calibrated (tared). The participant felt his center of gravity in the metatarsus area with a body position of slightly bend knees induced by the ski-boot geometry and an upper body forward lean, in which the poles did not touch the ground (see **Figure 3E**). The participant was instructed to stand in a dominantly upright position without applying contact force to neither shin nor calves. Here, the intention was to define a calibration procedure which can be easily transferred and performed under laboratory conditions as well as on the slope. For this calibration procedure no damped compensator (as presented in the research of Böhm and Senner, 2008) was utilized, as no significant differences were observed in the preliminary calibration tests of the force sensors. The calibrated values of the sensors revealed that the defined approach is reliable, consistent (cf. **Table 2**) and sufficiently accurate. Unwanted ski movements were not detected. After calibration, the sensor signals returned to baseline 0 N (of the Δ force) once the participant get to the calibration stand position.

Static pull positions where executed perpendicular to the ramp base position. The participant pulled slightly below shoulder height to maintain a natural skiing position. As the static center-weighted skiing position (standard position, SP) is concerned the measured knee angles resulted in mean flexion angles of 44 ± 10°[3]. Yoneyama et al. (2001) averaged at about 50°knee flex angle when comparing joint motion as well as reacting forces in the carving ski turn compared to a conventional ski turn. A similar ramp testing study (30°ramp covered with rubber) was conducted by Böhm and Senner (2008). Here, mean knee flexion angles of 45.8 ± 8.9° were determined.

2.3. Experiments on the Slope

The test runs where performed by a state certified Austrian ski/mountain guide and professional ski teacher (m = 75 kg; L = 178 cm). The usefulness of lightweight and simple systems in alpine skiing using IMUs[4] as well as dGNSS[5] sensors was underlined by recent studies of Gilgien et al. (2013), Gilgien et al. (2015), and Martínez Álvarez et al. (2019b). It was pertinent to combine IMU data with the non-intrusive characteristics of the lightweight force recording setup developed here. IMUs proofed to be useful to collect performance oriented skiing data from diverse body parts (Yu et al., 2016) to capture vibrations acting on the lower back using shank, thigh, sacrum, and sternum sensors

[3]Measurements were performed with a protractor, thus, accuracy is lower compared to an optical 3D tracking system using visual pointer markers.
[4]Inertial Measurement Units.
[5]Differential Global Navigation Satellite System.

FIGURE 2 | (A) Data acquisition system in a small backpack. **(B)** 3D-printed case of the DAQ system including the wiring of the sensor.

(Spörri et al., 2017) and to aggregate data to accurately (±0.06 m) estimate the athlete's CoM (center of mass) (Fasel et al., 2016). The non-intrusive way of using IMUs is a highlighted advantage in skiing and other sports (Camomilla et al., 2018) as the package of the units is small and light, wearable, easy to set-up and to analyse. The latter comprises the translation of scientific data and expert evaluation into useful coaching hints for the user (Brunauer et al., 2020). Furthermore, the model of an inverse pendulum can be applied depending on the sensor position to interpolate CoM kinematics (Gilgien et al., 2013, 2015). Consistently, Martínez Álvarez et al. (2019a) have demonstrated, that their developed turn detection device is a valid and robust tool based on gyroscope sensors[6]. To that effect, the authors used aggregated raw data of Snowcookie[7] IMU devices for the determination of position, speed and edging angles. Three IMUs were used, one positioned at the lower end of the sternum, the other two 5cm in front of the bindings' toepiece, resulting in additional 35 g each (55 g with mounting plate). The IMUs contain 9-axis motion sensors (gyroscope, accelerometer, magnetometer) and deliver data via Bluetooth data exchange standard (BLE 4.2).

[6]LSM6DS3, (2.5 × 3 × 0.83) mm, ±8 g, and ±500 dps full scale, STMicroelectonics, Amsterdam, Netherlands.
[7]https://snowcookiesports.com/startup-home-2/.

3. RESULTS

3.1. Tests Under Laboratory Conditions

3.1.1. Flat Land Weight Transfer

The first—most simple—test started in neutral position without significant force on shins or calves, followed by forward and backward leanings. In order to validate the ski boot system, the participant repeated every procedure multiple times after taring the system again on flat ground. Leaning forward and leaning backward revealed clearly force patterns apart from the heel sensor (see **Figure 5**), which reacted while rocking up and down rather than forward and backward leaning. The *range of motion* (ROM) of the up and down rocking movement while laying back is illustrated in **Figure 3A**, in which a slight, almost inevitable counter-movement of the upper body is noticeable.

The flat land weight transfer sequence shows that forces are transmitted in the boots shell mainly due to the constrained ankle joint (cf. **Figure 4B**). Despite leaning backwards, the forces on the heel sensor hardly increase. This indicates limitations of solely in-plane force measurements. To overcome this limitations, force sensors have to be placed within the inner surface of the ski

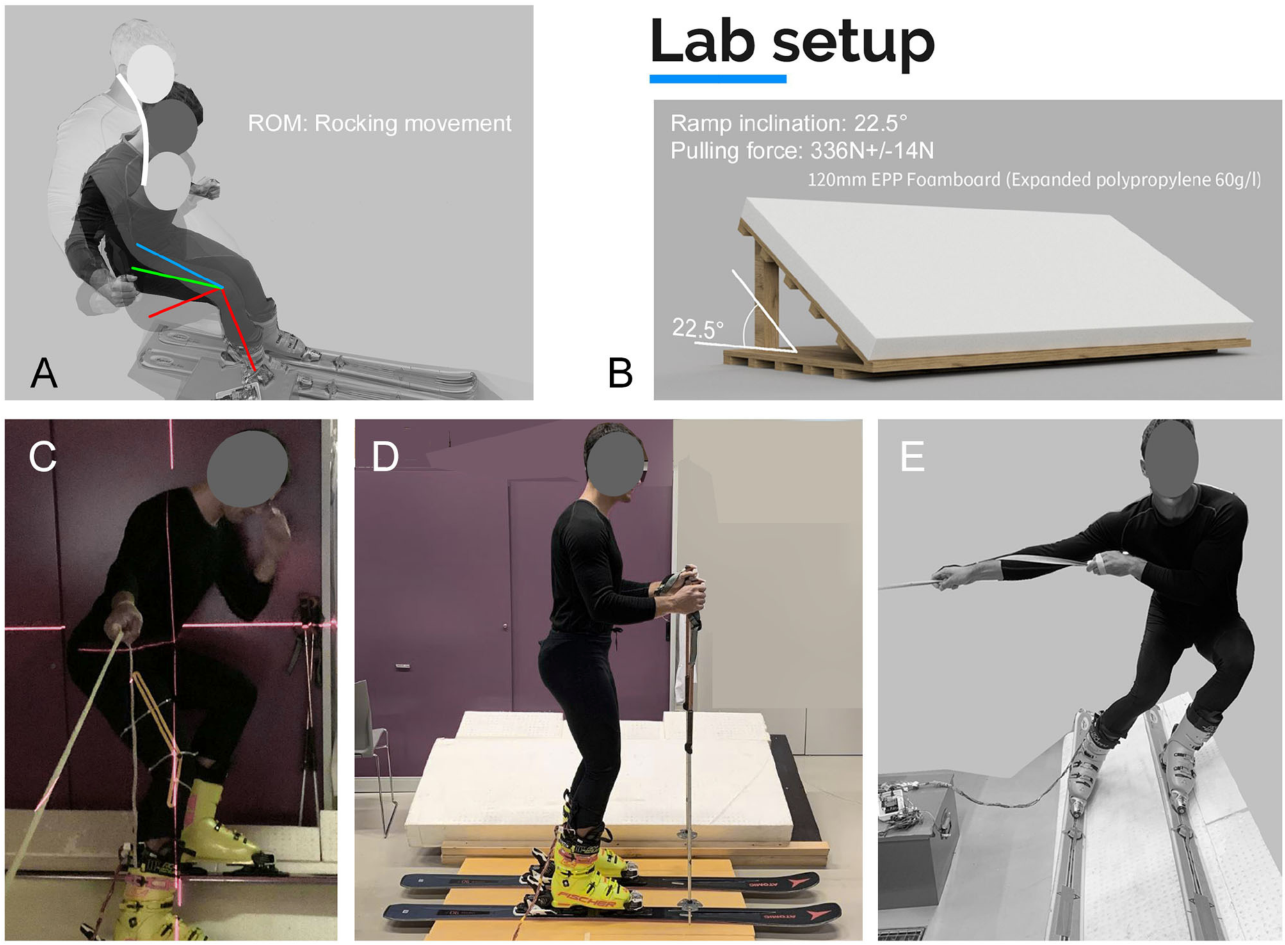

FIGURE 3 | Lab experimental setup: **(A)** ROM at lay back movement, **(B)** Ramp setup, **(C)** Measuring of body angles using laser level and protractor. **(D)** Tare position, **(E)** Body position while pulling up the resistance weight in central stance.

TABLE 1 | Testing sequence after level calibration.

Rocking motion level ground	Ramp pulling 336N	IRBP (see Figure 4)
Central stance	Central stance (**Figure 3E**)	BIAD (**Figure 4A**)
Lay back	Lay back	Slip-catch (flat)
Forward lean	Forward lean	Phantom foot (flat, ramp) (**Figures 4B,C**)
		Inside edge (flat) (**Figure 4D**)

TABLE 2 | Calibrated sensor (tare) values of preliminary test runs [N].

Run#	H	BL	BR	TR	TL	FR	FL
–	N	N	N	N	N	N	N
1	−57.38	−6.80	−36.67	−5.11	−6.88	−88.67	−148.00
2	−57.33	−8.87	−33.28	−5.00	−6.91	−115.67	−216.87
3	−57.24	−8.40	−35.54	−4.84	−6.15	−136.70	−247.11
4	−57.24	−8.01	−28.44	−4.83	−6.27	−124.59	−205.38
5	−57.27	−8.73	−33.13	−4.88	−5.48	−126.85	−209.10
6	−57.28	−9.11	−54.28	−4.91	−6.28	−126.44	−214.23

boot at the foot's and calf's contact areas. Additionally, the boot characteristics (e.g., ROM, boot stiffness represented by the *flex index*) influence the measured forces, significantly (Petrone et al., 2013; Hauser and Schaff, 2016). The ROM of the investigated ski boot is pictured in **Figure 4B**, where the participant is in a backward position with lifted heel and the right leg is rotated to the left-hand side. Thus, no force changes are detected at the heel sensor H and the right back spoiler sensor *BR* (see **Figure 5**).

3.1.2. Ramp Weight Transfer

The same procedure, as previously described in the flat land weight transfer test, was conducted on the ramp. In addition, a lateral force was applied by pulling a dead-weight of an equivalent force of 336 ± 14 N. The back spoiler/shaft sensors (*BL, BR*) detected force changes while forward and backward leaning with respect to the calibrated body position, however, the heel sensor *H* only reached a peak force of 162 N when the participant was rocking up and down in neutral position while the pulling force

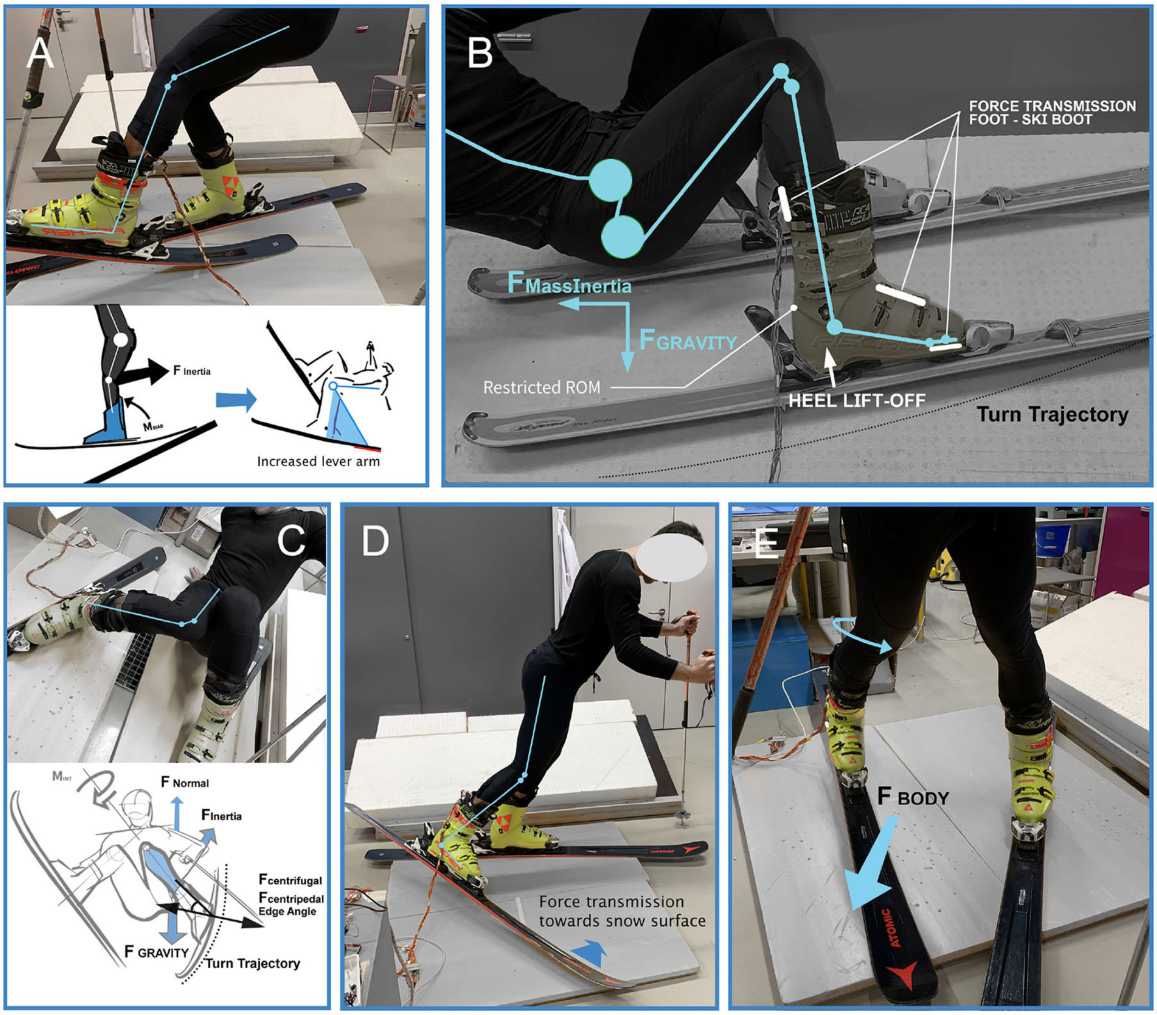

FIGURE 4 | (A) Quasi-statical BIAD force appliance to boot; **(B)** Skiers' range of motion influencing the sensor force loading; **(C)** Phantom Foot: Increasing strain from a low starting position; **(D)** Inside edge pressure raise (cf. VER); **(E)** Slip-catch stance.

was maintained (see **Figure 5**). The right upper toe sensor (*TR*) revealed small force deviations. The toe sensors showed strong force signals compared to the other body positions/movements, which is attributed to the direct force transmission in the forefoot area toward the ski.

3.1.3. Quasi-Static Boot Induced Anterior Drawer (BIAD)[8]

Figure 4D illustrates how the effect of mass inertia of the skier and the increased lever from the back end of the ski are resulting in anterior tibia movement in relation to the femur while the musculus quadriceps femoris, the quadriceps ligaments and the ligaments of the patellae are aligned almost linearly and directly apply strain to the whole knee structure. During this test, the participant was instructed to push the back of the right ski downwards to the ground. The loading can be seen in the strong bending curvature of the ski (see **Figure 4D**). It is assumed that the quasi-statical BIAD position gives a first impression regarding the force distribution over the ski boot, although dynamic force peaks are neglected in this study. As seen in **Figure 5**, row 3, the back spoiler sensors (*BL, BR*) are indicators of the ski's back-end loading.

3.1.4. Phantom Foot Position

From being in a severe but quasi-static valgus position of the knee joint (see **Figure 4C**), the loading was cautiously altered by the participant himself. Almost no pressure alteration is measured on the outside sensors/downhill side sensors. The most distinct signals come from the inside spoiler sensor *BL* which appear in combination with strong signals, partly exceeding the 200 N barrier, of the front sensors (*FL+FR*) (see **Figure 5**, row 4). Besides the participant felt a heavy loading in the inside-forefoot

[8]Boot-induced anterior drawer is a mechanism caused by a backward fall applying severe stress on the knee structures as a consequence of the skier's inertia and the stiff boot structure (cf. Johnson et al., 1983).

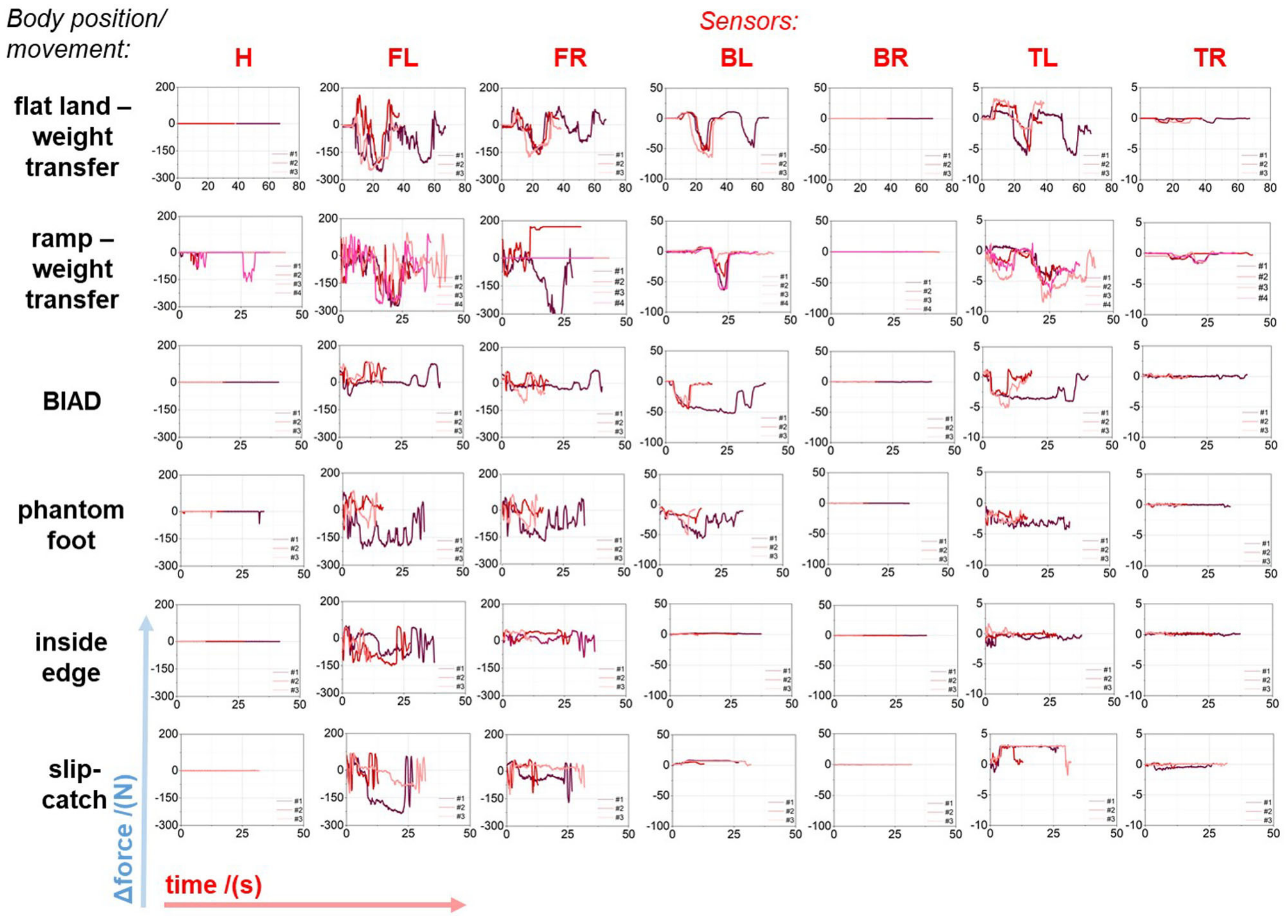

FIGURE 5 | Referenced force over test time diagrams of all sensors. The force is referenced prior each measurement by a standardized procedure. Multiple measurement cycles are illustrated. Six skiing situations were simulated under laboratory conditions (body position and movement). BIAD, boot induced anterior drawer; inside edge …VER; slip-catch …hyperextension of the knee joint.

because of generating counter-pressure to hold the position under enough tension of the lower body. The force peaks of the heel sensor (*H*) could be induced by applying counter-pressure to fight the knee valgus movement, respectively to put even more pressure on the ski's rear edge.

3.1.5. Inside Edge Pressure Raise and Slip-Catch Pose

The inside edge pressure raise position (*valgus-external rotation*) is shown in **Figure 4D**. In **Figure 5** the toe-induced reaction of the front sole sensors (*FL+FR*) is observed as distinct peaks (great toe presses downwards and to the inside), whereas the heel sensor (*H*) remained unchanged. Low force changes of about 4 N are observed at the left spoiler sensor (*BL*) which is traced back to calf rotation inside the boot. Also the slip-catch pose (*hyperextension of the knee joint*) revealed comparable characteristics in terms of the force changes. The slip-catch pose is a similar loading as the inside edge pressure (cf. **Figure 4E**) besides the lifting of the ski. Therefore, the measured force changes are in the same range and show related force patterns.

3.1.6. Conclusion Lab Tests

Regarding the constraining forces of a ski boot, the placement of the three insole sensors (two at forefoot region, one under the heel) should give a clear representation of the heavy forefoot loads. Overall ground reaction forces are transferred through the boot's cuff and spoiler, hence, lead to differences compared to force plate results (Cf. Lüthi et al., 2005; Stricker et al., 2010). Nakazato et al. (2011) have shown that pressure insole measurements tend to underrate the force values from 21 to 54% depending on several factors (turn phase, skiing level, slope, etc.) and that different loading patterns occur over loading and unloading cycles of the ski turn.

Range of motion (ROM) restrictions in addition avoid clear force characteristics in the heel region apart in the static tests. As illustrated in **Figure 4B**, a substantial amount of force of the skier's lower limbs in the system[9] is transferred across the upper spoiler and the instep areas into the ski boot's shell. The observation of merely pressure insole data becomes

[9]Skier—boot—binding—ski—ground.

difficult to interpret in back-weighted positions, because of the force transmission in above mentioned areas. The spoiler forces and the rotation of the bootleg seem to be reliable indicators of the skiers' balance along the sagittal plane. Therefore, the development of a sensor-equipped hinge element that measures angular position, angular velocity and the resisting forces in the end positions (forward lean, backwards lean) could be of great interest for future studies.

On the contrary, the lab tests and the deduced results provided insights, that sensors in the upper toe area solely represent values of low forces (i.e., not exceeding ±5 N). Though force changes related to body movements on the sagittal plane are observed, which are influenced by the multiple joints in the forefoot and especially by arbitrary toe movements. Force change peaks especially occur when spontaneously changing body position or when initiating a ski turn. It is advisable to re-position the upper toecap sensors (*TL, TR*) to higher loading positions for further experiments. For example, the *cabrio* or *overlap* designs of a modern ski boot hardly allow sensor positioning directly at the instep and above the metatarsal bones. Further structural changes to the ski boot have to be reconsidered for experimentation in the future.

3.2. Testing on the Slopes

The slope mainly has a steep incline of 25–35%. The edge inclination according to the Snowcookie data analysis resulted in 27°outside ski 40°inside ski for short turns in average (of the total number of short turns) and for longer turns 52°outside ski 56°inside ski were examined from the time integral of the gyro sensor data (see **Figures 6–8**; x-axis = axis along skiing direction/coronal plane, y-axis = steep incline of ski/sagittal plane, z-axis = rotation/transverse plane). The first two runs where performed at moderate speed alternating short turn and mid-to-long turn sections. Run **3** and **4** were performed with swing intervals increased forward lean and backward lean. Run **5** and **6** were performed at maximum speed with regard to the moderate steepness of the slope. **Table 3** lists the measured velocities (maximum and average) during riding on the slope including gliding passages of the slope. The data recording paused when the skier stopped and so were not included in the evaluated data (Snowcookie data were used to reference all recorded data).

All runs were executed with alternating phases of long turns and short turns. As the tests were done on public slopes and warm conditions (+2°C), the rider had to adjust his individual lines as illustrated in **Figure 9**. Furthermore, this figure shows the sections the authors picked from all six runs to showcase detailed views. **Figure 10** showcases still footage of forward lean, lay-back and centered skiing as described below:

The results of the recorded force changes are shown for different runs and sections (see **Figure 9**). Taring results and overall forces during skiing indicate that the sensors on the insole and the spoiler are reliable and sufficiently accurate for this descriptive study. DAQ resolution and frequency (cf. section 2) are adjusted in order to detect turns and balance parameters. The force sensor data were correlated to the Snowcookie data and analyzed in the following. In the following diagrams, the run-time dependent change of the (calibrated) Δforce of the sensors TL and TR are omitted as they confirm the results of the laboratory ramp test and reveal low measured forces. In addition, the measured data are highly scattered, mostly, leading to non-conclusive patterns. The back spoiler sensors (*BL, BR*) were combined as differences in the calf shapes, the individual knee position, respectively the boot's canting[10] seemed to influence the loading contribution strongly in this setup. The insole sensors (*FL, FR, H*) revealed clear force changes and demonstrated the strong influence of the toes, respectively the forefoot.

3.2.1. RUN 1 and RUN 2: Regular Skiing: Long Turns and Short Turns Intervals

The spoiler sensors (*BL+BR*) demonstrate that there are slight forces changes in a range of 50 N (see bold red line in **Figure 3**). Force peaks are reached close to the highest inclinations of the x-axis (ski direction) (black thin line) of the right turn (inside boot) already accelerating the ski toward a left turn. Interestingly, the toe sensors (*TL+TR*) reach their force peaks just before the heel sensor which can be associated with a central balanced stance on the skis and the turn initiation by transferring force and inclination toward the front edges of the skis. Because of the neutral stance while taring, the back sensors even show slightly positive values (less force, unloading) at the swing changes and the beginning of the turns.

3.2.2. RUN 3 and RUN 4: Forward Lean Skiing and Skiing With Weight Backwards

The third and fourth runs were executed alternating with extensive forward lean as well as with backwards shifted weight. The sole sensors (*H, FL+FR*) revealed no significant force deviations, however the force patterns from run 3 and 4 are different as the timing of the swing release is varied and the ski acceleration differs. The sole sensors are depending on edging angle and acceleration forces while the back spoiler sensors (*BL+BR*) relate more directly to body position. The back spoiler sensors clearly show deviating force peaks, partly exceeding forces of 200 N, as seen in the back-weighted skiing sections of **Figure 7**. This is of particular interest for further studies, where detailed correlations of actual body position to force change patterns have to be drawn.

3.2.3. RUN 5 and RUN 6: Fast Skiing

Run 5 and 6 were performed at higher speeds and a more radical deceleration on the transition from long turns to the short turn phase. Overall, the steep incline of the slope was moderate and more edge force would have led to deceleration and despite that, the force peaks on the insole positioned heel sensor (*H*) reveal significantly higher force changes as expected. For faster skiing the weight transfer from (*FL+FR*) toward (*H*) at the end of the turns becomes clearer.

[10]The cuff canting adjustment of the lateral tilt enables the skier to tune the boot geometry to the specific leg morphology.

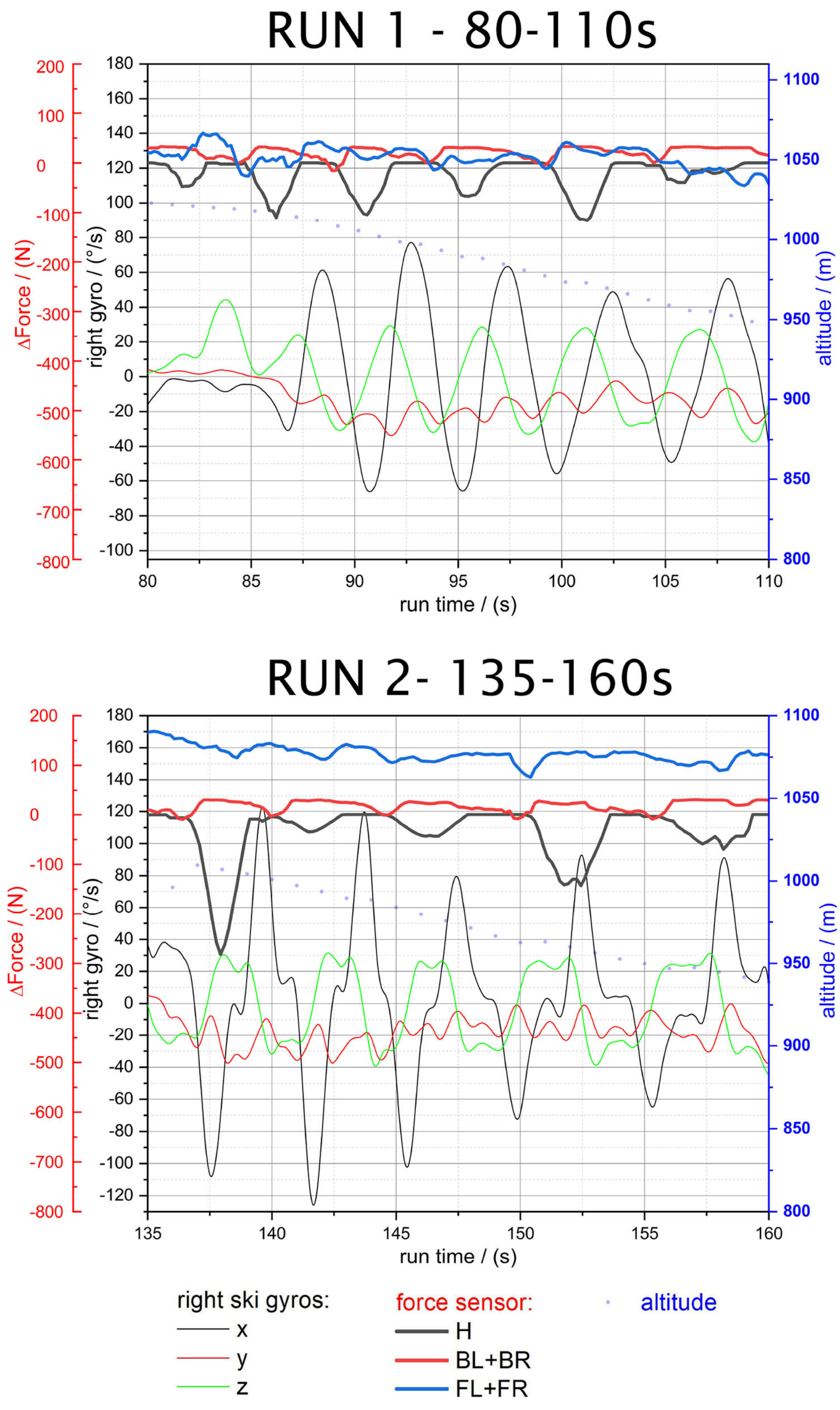

FIGURE 6 | Run 1—80–110 s and Run 2—135–160 s.

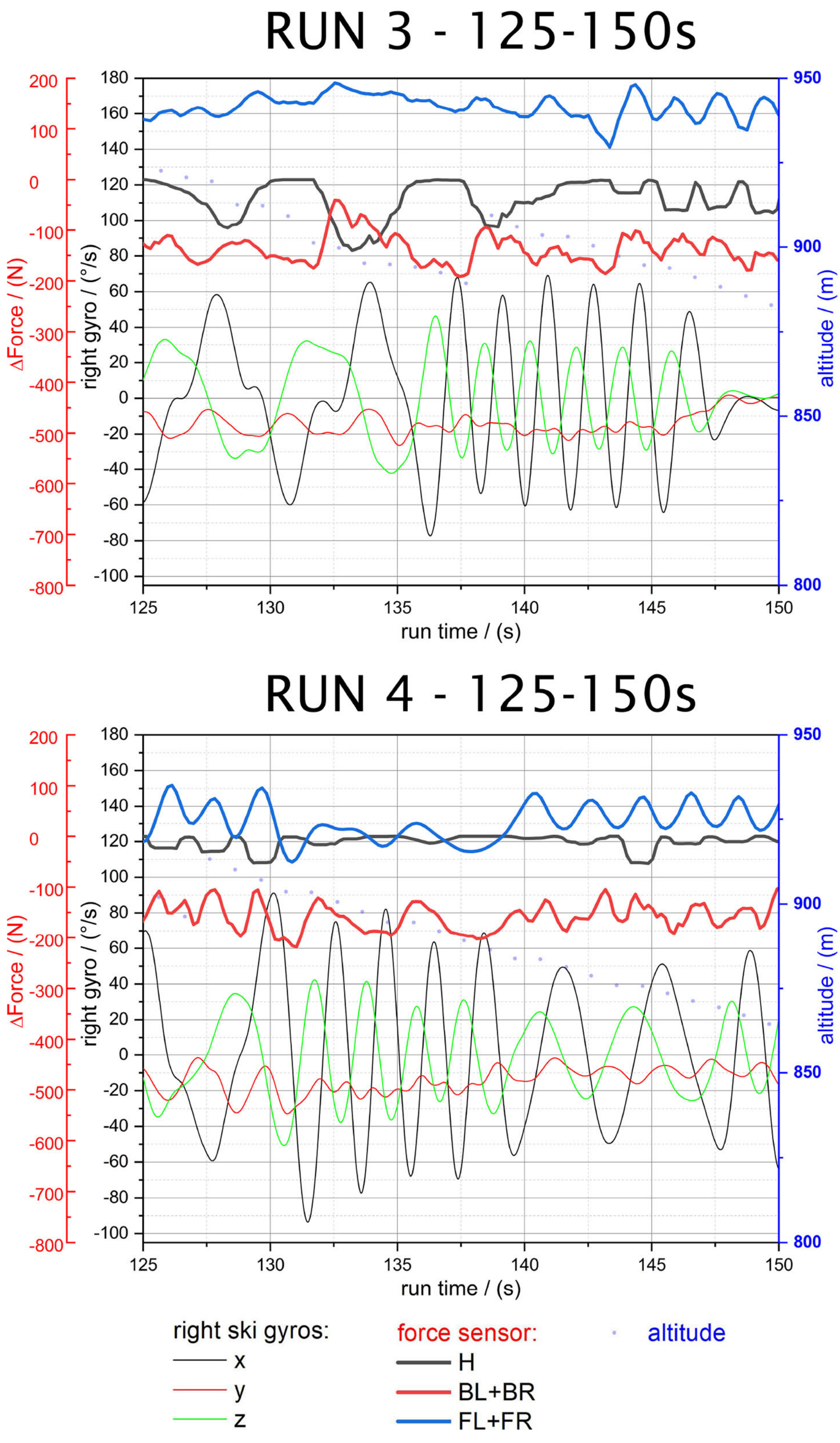

FIGURE 7 | Run 3—125–150 s and Run 4—125–150 s.

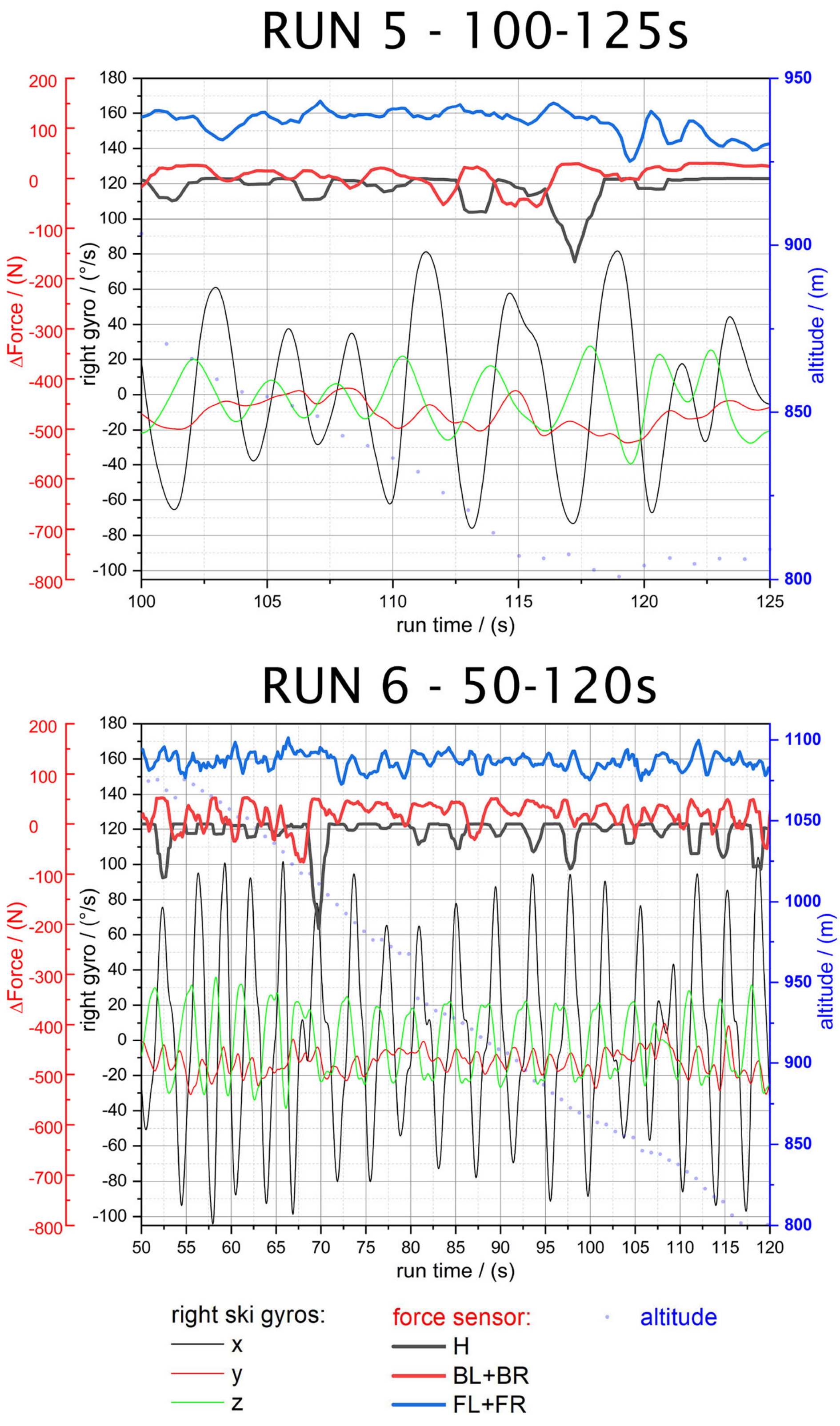

FIGURE 8 | Run 5—125–150 s and Run 6—50–120 s.

3.2.4. Conclusion Slope Tests

3.2.4.1. Toe induced turn release

The release of the short swing turns as well as the long radius turns is often indicated by a quick force increase of the sensors *FL* and *FR* and the direction change is linked to a general reduction of ground reaction forces (*FL, FR, H*).

3.2.4.2. Backward lean

Backward lean has to be considered in relation to the slope inclination and becomes obvious during a loading phase of the ski turn (*BL, BR*). Further sensor units positioned on the instep and directly at the hinge could give further informative data about the body position. Therefore, the overall structure of an instrumented (smart) ski boot for further testing has to be optimized.

3.2.4.3. Less force peaks on heel as initially expected

Due to the strong form fitting of a modern ski boot, the heel gets levered upwards because of the direct contact of the instep and the restricted ROM influenced by many parameters, such as cuff height, cuff geometry, hinge point, material properties, temperature, among others. In that regard, torque measurement in the boot's hinge, comparable to bicycle power-meters, could give more information about the boot's stress loads and deformation.

TABLE 3 | Maximum and average velocity of each run on the slope in [km/h].

Run#	Max. velocity	Average velocity
–	km/h	km/h
1	59.9	34.2
2	58.9	36.1
3	50.9	36.2
4	55.2	36.1
5	87.1	53.0
6	74.7	53.1

4. DISCUSSION AND OUTLOOK

The aim of this study was to assess piezoresistive sensors and their positioning (**Figure 1**) within the ski boot to study whether or not force changes as well as patterns are observable regarding skiing balance, riding style or severe (injury related) body positions. The sensor positions are of particular interest for a future injection-molded boot design produced by inserting the sensors directly into the mold prior to the polymer injection. Additionally, the positions were chosen to gain insights of injury related movement patterns. Our results reveal that force patterns for specific body positions as well as movements can be derived and regarding the positioning of the sensors the conclusion is that the toecap (upper foot; *TL, TR*) sensors are not essential to derive force patterns at their current position. This was examined under laboratory conditions as well as on the slope. A positioning further toward the instep, respectively above the metatarsal bones, will lead to more consistent results. Consequently, the noise of the data by arbitrary toe movements while skiing will be reduced. For athletes and, especially, young athletes, the back spoiler sensors (*BL, BR*) and the toe sensors (front sole; *FL, FR*) in combination with the data of accelerometer and GPS can highlight athletes the efficiency and more importantly the force acting on the ski boots toward the end of a turn when acceleration by subtle

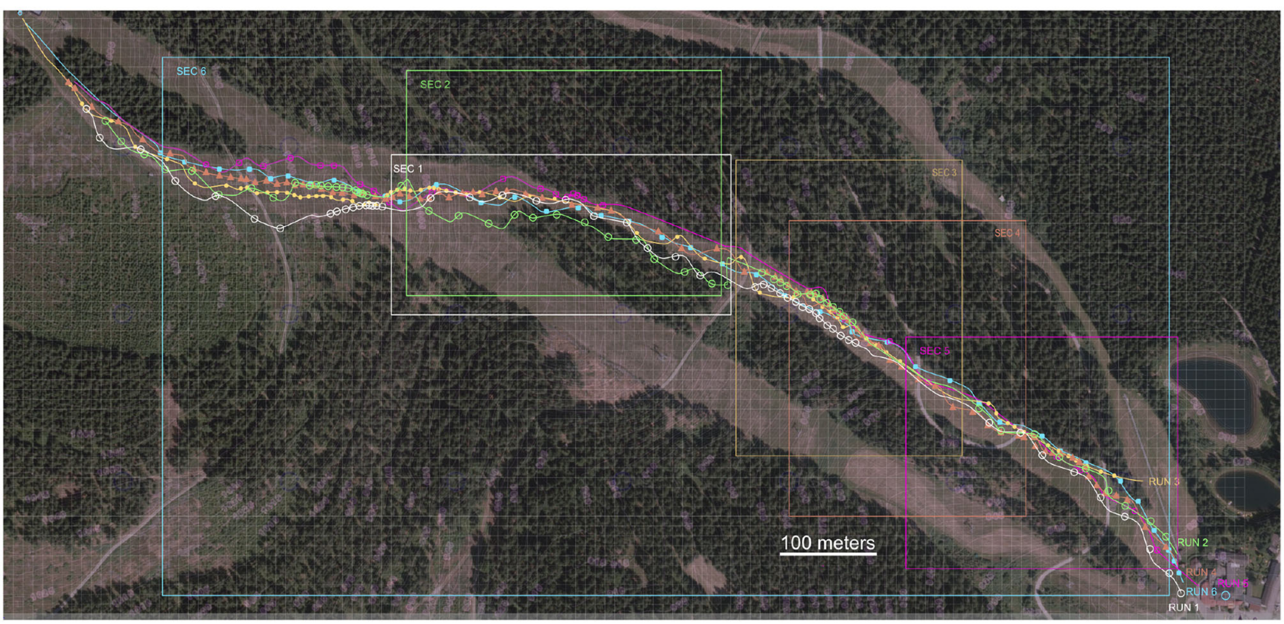

FIGURE 9 | Overview of six runs—each section marks the range of the detailed run analysis as shown in the diagrams from **Figures 6–8**.

FIGURE 10 | Still frames from video footage: **(A)** Forward lean skiing. Strong upper body overhang with overdone steering initiation via the ski's shovel **(B)** Lay-back positions with center of mass clearly behind the foot area. Upper movement necessary to initiate a turn. No distinct hip bend and no clear longitudinal foot separation (skiing direction). Nonetheless, a slight forward lean during the turn transition was necessary. **(C)** Balanced skiing with clear hip bend and compact body position. The body extends during the turn transition and unloading of the skis.

weight transfer is desired. Especially, accurate location tracking technology already provides valid data about ground reaction force (GRF), air drag and snow friction in ski racing (Gilgien et al., 2018) and might help the analysis of force data in future in regards of external forces and risk evaluation. Moreover, it is necessary to measure a wide force range with calibrated piezoresistive sensors rather than only the distribution of the skiers weight (without considering inertia effects). This approach is a further development of pressure insoles as well as devices that measure body position (some commercial products are recently available[11]). As those devices actually measure weight distribution over a sensor map, algorithms can help skiers to gain deep insights about their skiing, immediately.

[11]For winter season 2019/20 a product called *Carv* was released. https://getcarv.com/app.

Further research has to be conducted to analyze the presented ski boot with sensors in terms of limitations, temperature dependent force changes due to the inherent viscoelasticity (i.e., loading rate, humidity and temperature dependent behavior) of the boot material. To that effect, the influence by the strong form-fitting of the stiff ski boots shows significant influence on the measured forces (force paths) and has to be studied in detail by optical full-field strain analysis under loading. Beyond this qualitative study, a further matching with optical systems that are capable of capturing motion in 3D space (Federolf, 2005; Spörri et al., 2016; Rhodin et al., 2018) has to be analyzed in future studies to render more accurate bio-mechanical conclusions.

Furthermore, this study has to be extended by increasing the participants (skiers) with variations of skiing level, style, age and gender in order to investigate representative results statistically (hypothesis test for bias and Pearson's correlation coefficient). One challenge for this representative study will be the preparation of ski boots in different size. The next step would include a feasibility study for a manufacturing process, such as injection molding technology, that enables the sensors to be safely molded within the ski boots' shell while being protected by a suitable material matrix (cover). This would also involve the testing of fatigue phenomenons of sensors, boot materials and the analyses of the boot stiffness in comparison with the common ski boot model. A new design of a ski boot would be necessary to find an optimized purpose-driven form for measuring skier related forces in the boot.

Future findings should show more clearly how ski binding release could work, as there are many options to integrate electro-mechanical release systems into the ski-binding-boot-system (SBB). A holistic understanding of skiing safety is therefore required. With this, a predictive (AI-algorithms based) binding system can be implemented in an electro-mechanical binding. The authors are convinced that this can contribute to rethink current standards of alpine safety products. Skier, basically, have a lot of trust to the reliance of state-of-the-art mechanical bindings. Also it seems that skiers have a greater awareness of anterior cruciate ligament (ACL) injuries. That is why the combination of a basic mechanical solution and an additional electro-mechanical release device could be an intermediate step to gain the customer's trust for smart electro-mechanical (IoT) release solutions. Additionally, the development of a smart cuff-hinge has to be considered in future for several reasons: (i) a sensor at the hinge can monitor forces as well as torques during cuff rotation (tibia position); (ii) a sensor-equipped cuff hinge will be independent of boot size and boot model, consequently, sensor data can be interchanged; (iii) there is already proven technology commercially available for other sports (e.g., power measurement in the crank axle of bicycles or oarlock power-meters in rowing). As the authors investigate ski binding release action (Nimmervoll et al., 2021) and the potential of a binding plate with lateral release functionality, this work already delivers important data as a preparatory study. Predictive data analysis can give the skier feedback about the release settings. The skier can see how close a situation came toward release in regards of occurring forces and what happened when, for example, accidental release happened considering as a false positive. This can lead to individual release profiles also adjustable to the utilization of the ski equipment (e.g., park, back-country, slope, race, couloirs). By utilizing an electro-mechanical binding plate with an adjusted retention force, lateral release in certain situations can be unlocked and locked within milliseconds without sacrificing the qualities of state-of-the-art mechanical bindings. Binding elasticity[12] is a crucial attribute of mechanical bindings to avoid false positive events and can save the skier from dangerous falls. Safety ski bindings are designed to release during the forward fall (heel piece releases upwards) and during a forward fall with body rotation (toe piece releases side-wards). Regarding this basic functionality, bindings are more unlikely to release in backward-twisting falling situations. The assumption is, that a laterally releasing binding plate can assist a mechanical binding to the overall release forces in certain situations dependent on the real-time measurement of certain in-boot sensors.

The potential of measuring forces inside the ski-binding-boot-system can be considered on several levels and always in combination with other environmental data (e.g., steep incline, body position, force acting on the ski boots). This study contributes to the visionary idea of measuring the skiing speed and acceleration (dGNSSR/GPS, 6-axes DOF accelerometer) in real-time and triggering, beyond an electro-mechanical ski release binding, the following: (i) helmet airbags and stiffening joint protector to restrict the body's range of motion during falling; (ii) high loads with severe backwards or forwards lean can trigger, among other signals, a mechanism for lateral binding release and adaptively reduce the release force values. Furthermore, smart bandages/protectors can be utilized to stiffen vulnerable body areas (e.g., knee joint) and restrict the ROM to avoid hyperextension and hyperflexion when overloads are detected. These and other developments of ski bindings, ski boots, and other wearable equipment will help to increase the safety of skiers and provide force pattern analyses of turn initiation and acceleration, which is particularly beneficial for the development of skiing technique for (young) athletes.

[12]Travel of the binding before it releases the boot.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent was obtained from the individuals Florian Nimmervoll, Umut Çakmak, and Alwin Mold for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

FN and UÇ contributed to the conceptualization of the study, the prototyping, the testing, and the analysis. MR contributed to the prototyping. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2021.557849/full#supplementary-material

Supplementary Video 1 | Lab test-weight transfer and taring position.mp4.

Supplementary Video 2 | Slope test.

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