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Sex-specific biomechanical profiles in recreational alpine skiing: an integrated analysis of kinematics, muscle activation, and plantar pressure

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ABSTRACT

While epidemiological data highlight higher knee injury rates among female alpine skiers compared to male skiers, particularly anterior cruciate ligament ruptures, biomechanical risk factors remain underexplored. This study investigates sex-specific biomechanical differences in recreational skiers to clarify potential disparities in movement strategies between sexes. Sixteen recreational skiers (nine females, seven males) performed standardized skiing tasks while joint kinematics, muscle activation, and foot forces were measured bilaterally using inertial sensors, surface electromyography, and pressure insoles, and analyzed separately for the inside and outside leg. Results showed distinct movement strategies between sexes. Males exhibited a "hip-dominated" steering strategy, with greater bilateral knee and ankle flexion ($p < 0.001$, $d = 0.65$ and 0.72, respectively), outside hip internal rotation ($p < 0.001$, $d = 1.21$), and bilateral biceps femoris activation ($p < 0.001$, $d = 0.72$–0.78). Conversely, females relied on a "knee-dominated" strategy, exhibiting increased valgus at the outside knee ($p < 0.001$, $d = 1.18$), greater rectus femoris activation in the inside leg ($p = 0.005$, $d = 0.52$), and higher forefoot plantar pressure on the outside limb ($p < 0.001$, $d = 0.64$). These sex-specific movement strategies may inform future prospective research on biomechanical risk factors for knee injuries in recreational alpine skiers. The results highlight the potential value of sex-specific training programs emphasizing balanced muscle co-activation and of equipment design considerations tailored to female-specific movement strategies.

1. Introduction

Alpine skiing is a sport that combines physical strength, coordination, and a high degree of risk management, exposing skiers to significant biomechanical loads and a substantial risk of injury, particularly to the knee (Wagner et al., 2023). Epidemiological data have consistently shown a clear difference in injury risk between sexes, with females exhibiting a higher prevalence of knee injuries than males (Ammerman et al., 2024; Bhatt et al., 2025), especially among recreational skiers (Blanke et al., 2016; Ruedl et al., 2023). Specifically, anterior cruciate ligament (ACL) rupture is considered the most common orthopedic injury, with a significantly higher incidence in female recreational skiers (79.20%) than in their male counterparts (56.35%) (Shi et al., 2020), while males predominantly injure their medial collateral ligament (Ammerman et al., 2024).

With respect to the possible injury risk factors and how they may differ between men and women, although in other sports it has been shown that the hamstrings-to-quadriceps ratio, which might influence joint stability and injury risk, differs between sexes (Korpinen et al., 2025), in alpine skiing this difference between men and women has only recently been demonstrated in elite skiers (Alhammoud et al., 2019). In the recreational context, the scientific literature has not yet

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explored sex-specific biomechanical differences in alpine skiing. Most studies have focused on epidemiological aspects and extrinsic risk factors, such as injury incidence, snow conditions, slope characteristics, and equipment properties (e.g., ski stiffness and binding settings), leaving a notable gap in understanding the underlying biomechanical risk factors. In this area, there is a significant lack of integrated data that connects parameters such as joint angles, muscle activation, and forces exerted during skiing. While some research on elite athletes has shown that performance and external loads, such as ground reaction forces and joint moments, can differ between male and female skiers, even when they tackle the same course (Alejo et al., 2021; Alhammoud et al., 2020), it is not clear whether and how these differences manifest at the recreational level and what implications they have for movement biomechanics.

Previous research has consistently reported sex-related differences in lower-limb biomechanics during dynamic sport tasks (Bencke et al., 2018; Decker et al., 2003; Powers, 2010). While other lower-limb kinematic-related variables also contribute to movement strategy, dynamic knee valgus (DKV) and rectus femoris (RF) activation are the variables most consistently shown to differ between sexes in dynamic sport tasks (Hu et al., 2023), and together they capture both the kinematic outcome and the neuromuscular origin of sex-related differences in movement strategy (Powers and Fisher, 2010). DKV is the kinematic expression of lower-limb neuromuscular control: individuals exhibiting DKV rely on an anterior-chain-dominant approach to managing joint loads rather than a coordinated strategy that distributes forces across the entire kinematic chain (Hewett et al., 2005). Accordingly, individuals with DKV exhibit systematically different muscle activation patterns than those without (Khou et al., 2024). RF activation represents the electromyographic correlate of this pre-programmed, quadriceps-dominant motor strategy (Shams et al., 2022), capturing the neuromuscular origin of the same movement pattern that DKV expresses kinematically.

Whether these sex-related differences extend to recreational alpine skiing and whether they form part of a broader, identifiable sex-specific movement strategy remains unknown. The main research question of this study was therefore whether male and female recreational alpine skiers employ different movement strategies during skiing. We therefore formulated two specific hypotheses: female recreational skiers would exhibit (1) greater dynamic knee valgus and (2) greater rectus femoris activation than their male counterparts. Additionally, an exploratory analysis of foot force distribution was conducted to further characterize these profiles. Identifying sex-specific movement strategies may inform future prospective research on targeted training programs, injury risk mitigation, and equipment design.

2. Materials and methods

2.1. Participants

Sixteen recreational skiers (nine females and seven males) participated in this study. Inclusion criteria required participants to have no history of musculoskeletal injuries in the previous 12 months and to possess a technical skill level of 5–7, according to the Italian technical progression for alpine skiing (FISI, 2018). Exclusion criteria included a history of cardiovascular, metabolic, or neurological conditions and the use of medications known to affect neuromuscular function. All participants reported no health conditions affecting physical activity at the time of data collection. Groups and ski equipment characteristics are reported in Table 1. Participants were matched for technical skill level, which was prioritized as the primary matching criterion given its direct influence on biomechanical parameters during skiing. The local ethics committee approved the study protocol and ensured compliance with the Declaration of Helsinki. Before data collection, all participants were adequately informed about the experimental procedures and provided written informed consent to participate.

Table 1
Participants and ski equipment characteristics. Data are shown as mean ± standard deviation (SD).

	N	Age (years)	Weight (kg)	Height (cm)	Skiing level	Ski length (cm)	Ski radius (m)
Female	9	23.8 ± 3.4	61.8 ± 7.2	164.3 ± 3.6	6.2 ± 0.8	165	13
Male	7	43.6 ± 13.7	74.6 ± 4.5	175.4 ± 4.7	6 ± 0.8	175	16

2.2. Materials

Kinematic data were collected using an inertial measurement unit (IMU) system (Xsens Awinda, Movella, Henderson, USA; sampling frequency 60 Hz). 15 sensors were positioned on the head (secured to the helmet), sternum, and pelvis, and bilaterally on the shoulders, upper arms, forearms, upper legs, lower legs, and feet (mounted on the ski boots). Surface electromyography (EMG) signals were acquired using a wireless system (MiniWave, Cometa srl, Milan, Italy) at a sampling frequency of 2000 Hz. Electrodes were placed bilaterally, after shaving and cleaning the skin with alcohol, on the rectus femoris (RF), biceps femoris (BF), and erector spinae (ES) muscles, according to SENIAM recommendations (Hermens et al., 2000) and on the external oblique (EO), approximately anterior to and mid-way along a line drawn from the lateral pelvic crest to the lateral lower ribcage parallel to muscle fiber orientation (Vera-Garcia et al., 2010). Foot forces (FFs) were measured using a three-zone pressure insole system (i.e., posterior, anteromedial, and anterolateral) (PIs; Loadsol, Pedar, Novel, Munich, Germany; sampling frequency, 100 Hz) placed inside the ski boots. All runs were video-recorded using a high-frequency camera (GH5S, LUMIX, Panasonic Corp., Osaka, Japan) set at a 100 Hz frame rate and full HD resolution, positioned at the bottom of the slope, facing forward. All measurement systems were synchronized through a custom-built microprocessor that generated a trigger at recording onset, which was captured by the sensor and displayed as a visual signal in the video recording, aligning the video with the sensor's data.

2.3. Protocol

Data were collected on the “Marc Girardelli” slope at Passo Monte Croce (BZ, Italy), a medium-difficulty ski slope. Visual references with small poles were placed 20 m apart, with 6 m of lateral offset along the course, to standardize skiers' trajectories and ensure a fixed number of turns per run (Fig. 1A). Each participant completed four descents, with a recovery period corresponding to the chairlift ascent time (5 min) between runs, consistent with real-world recreational skiing conditions. Subjects were instructed to ski at their best performance level, as assessed and verified by a certified ski instructor before data collection. Before on-slope measurements, the IMU system was calibrated on a flat surface according to the manufacturer's standard procedure, and maximal voluntary contraction (MVC) tests were performed for EMG normalization. Isometric MVCs were obtained as follows: for RF, seated with knee extension at 110° and hip at 90°; for the BF, prone with knee flexion at 90°; for the EO, supine in trunk flexion and rotation with the shoulders elevated off the surface; and for the ES, prone in back extension with shoulders lifted off the surface. EMG activity was recorded bilaterally for the four muscles of interest.

2.4. Data analysis

Joint kinematics were recorded in three planes (flexion–extension, abduction–adduction, and internal–external rotation) at the trunk, hip, knee, and ankle, using the MVN Analyze Pro 2024 software (“full body no hands” model; Xsens Technologies, The Netherlands), which applies an internal sensor fusion algorithm to compute joint angles. All joint

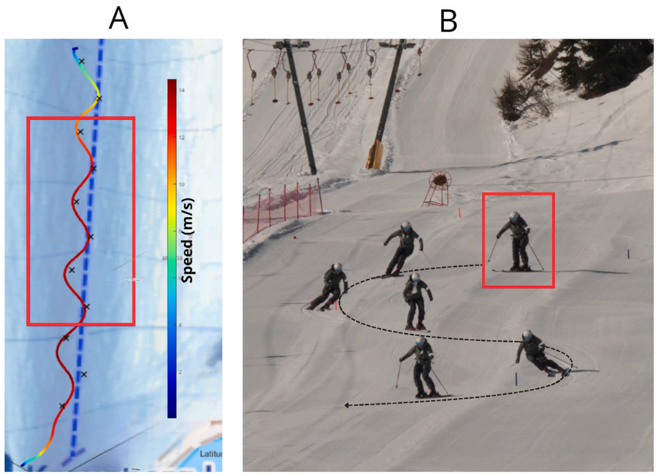

Fig. 1. Experimental setup. (A) The x markers represent reference points placed along the slope. The color map indicates the speed and trajectory recorded by GPS during the descent of one participant. The red rectangle identifies the acquisition zone, whose data were analyzed. (B) Sequence of frames showing two turn cycles. The red rectangle highlights the reference position used to define time 0 of the turn cycle. The dashed line represents the subjects' trajectory. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

angles were computed using ISB-compliant joint coordinate systems as implemented in MVN Analyze Pro 2024, following the recommendations of Ge Wu et al. (2002). Joint angles were expressed as Euler angles relative to the proximal segment, following the Joint Coordinate System proposed by Grood and Suntay (1983), with the sequence flexion–extension, abduction–adduction, and internal–external rotation for each segment. Due to the rigid structure of ski boots, which constrains ankle movement in the frontal and transverse planes, ankle abduction–adduction and internal–external rotation were minimal and were therefore excluded from the analysis. The raw EMG signals were filtered with a second-order Butterworth bandpass filter (20–500 Hz), and artifacts were removed if the signal exceeded an upper or lower threshold computed as the root mean square (RMS) ± 6 × SD, as described by Alhammoud et al. (2022). RMS was then normalized to MVC. FFs were normalized to the subject's body weight (BW) and analyzed as forefoot, rearfoot, and total FF components.

Turn cycles were identified by expert video analysis, with the zero-point corresponding to the moment when skis were flat on the snow with no edging angle (Klous et al., 2012) (Fig. 1B, red square frame). This moment coincides with the instant at which the load difference between the inside leg (IL) and outside leg (OL) reaches its minimum or crosses zero (Martínez et al., 2020), as the previously unloaded IL begins to take over as the new OL of the subsequent turn. The video-based reference points were double-checked with PIs' data using this force crossover criterion, following the best practices described by Martínez and colleagues (2021). Turn cycles were then automatically extracted using the zero-point identification procedure described above. Each turn cycle was subsequently time-normalized to 100 data points. Maximum (MAX) and minimum (MIN) values were extracted from joint angular excursions and compared between groups using the Mann–Whitney *U* test, following confirmation of non-normal distribution via the Shapiro-Wilk test. For FFs, only the peak value was extracted and compared in the same way. A permutation-based max-statistic method (1000 iterations) was applied to control the Family-Wise Error Rate and adjust for multiple comparisons while preserving the inherent correlation structure and the lack of independence among variables. Statistical parametric mapping (SPM, spm1d.org) was applied to compare continuous data across the turn cycle (Alhammoud et al., 2019). For SPM analyses, the critical threshold was determined using Random Field Theory, which inherently accounts for multiple comparisons across the temporal domain of the turn cycle, consistent with established SPM methodology (Pataky, 2010). Effect sizes are reported alongside all p-values to support robust interpretation. The alpha threshold was set at $\alpha = 0.05$ for all analyses. Data processing, statistical analysis, and figure generation were performed using MATLAB 2024b (MathWorks, Natick, MA, USA) and GraphPad Prism8 (GraphPad Software, San Diego, CA, USA). According to the Sex and Gender Equity in Research guidelines, the term *sex* is used throughout this paper to refer to biological differences.

3. Results

3.1. Joint angular excursion

Ankle angle was more flexed in the male group compared to the female group for MAX and MIN values in both legs (all $p < 0.001$; MAX-IL $r = 0.37$, MAX-OL $r = 0.43$, MIN-IL $r = 0.35$, and MIN-OL $r = 0.41$) (Fig. 2A). SPM analysis confirmed these results, showing a higher flexion in males across all turn cycles in both legs ($p < 0.001$, $d = 0.72$).

Knee angle showed greater flexion in the male group compared to the female group for MAX and MIN values in the IL (both $p < 0.001$, $r = 0.36$ and $r = 0.31$, respectively), while the OL differed only in the MIN value ($p < 0.001$, $r = 0.39$) (Fig. 2B). SPM analysis confirmed these results, showing greater flexion in males than in females across all turn cycles in the IL ($p < 0.001$, $d = 0.65$). In contrast, in the OL, differences were consistent from 32% of the turn cycle onward ($p < 0.001$, $d = 0.64$). Knee rotation movement showed differences in the IL's MAX value ($p = 0.017$, $r = 0.23$) and MAX and MIN values in the OL (both $p < 0.001$, $r = 0.46$ and $r = 0.32$, respectively) (Fig. 2C). Accordingly, SPM showed differences in the first and last 7% of the turn cycle for the IL ($p = 0.041$, $d = 0.63$ and $p = 0.046$, $d = 0.53$, respectively), while the outside knee resulted in a more intrarotated position in females compared to males throughout all turn cycles ($p < 0.001$, $d = 1.21$). Abduction movement showed differences in MAX values for both legs (IL: $p < 0.001$, $r = 0.43$; OL: $p < 0.001$, $r = 0.68$), but not in MIN values (Fig. 2D). SPM analysis revealed slight differences in the first 9% of the turn cycle for the IL ($p = 0.041$, $d = 0.69$) and significant differences in the OL from 10% till the end of the turn cycle ($p < 0.001$, $d = 1.18$), with females exhibiting a more pronounced knee valgus position compared to males.

Hip angle showed greater flexion angle in the male group compared to the female group for MAX ($p < 0.001$, $r = 0.49$) but not MIN values in the IL, while no difference were found in the OL (Fig. 2E). SPM analysis revealed a higher degree of flexion in males, ranging from 24 to 91% of the turn cycle, in the IL ($p < 0.001$, $d = 0.71$), whereas in the OL, no significant difference was observed. Rotation showed differences in the IL's MAX value ($p < 0.001$, $r = 0.41$) and MAX ($p < 0.001$, $r = 0.55$) and MIN in the OL ($p < 0.001$, $r = 0.33$) (Fig. 2F). SPM showed differences in the first 16% of the turn cycle for the IL ($p = 0.037$, $d = 0.91$), while the outside hip resulted in a more intrarotated position in males than females throughout all turn cycles ($p < 0.001$, $d = 1.21$). Hip abduction showed no difference, neither in the discrete comparison (Fig. 2G), nor in the SPM analysis.

Trunk flexion–extension showed greater MAX values in females compared to males ($p = 0.049$, $r = 0.16$), but not MIN values; moreover, a higher lateral leaning (abduction) was highlighted in the male group compared to the female group ($p = 0.042$, $r = 0.19$) (Fig. 2H). SPM showed more flexed angle in females than males, only in the first quarter of the turn cycle ($p = 0.02$, $d = 0.51$), and higher rotation in males in the first 5% ($p = 0.047$, $d = 0.54$). In contrast, females had greater values than males from 66% of the turn cycle onward ($p = 0.006$, $d = 0.72$), and a higher degree of leaning in the male group compared to the female group from 25 to 83% of the turn cycle ($p < 0.001$, $d = 0.83$).

3.2. Muscle activity & force distribution

SPM analysis did not show differences in EO, ES activation in either

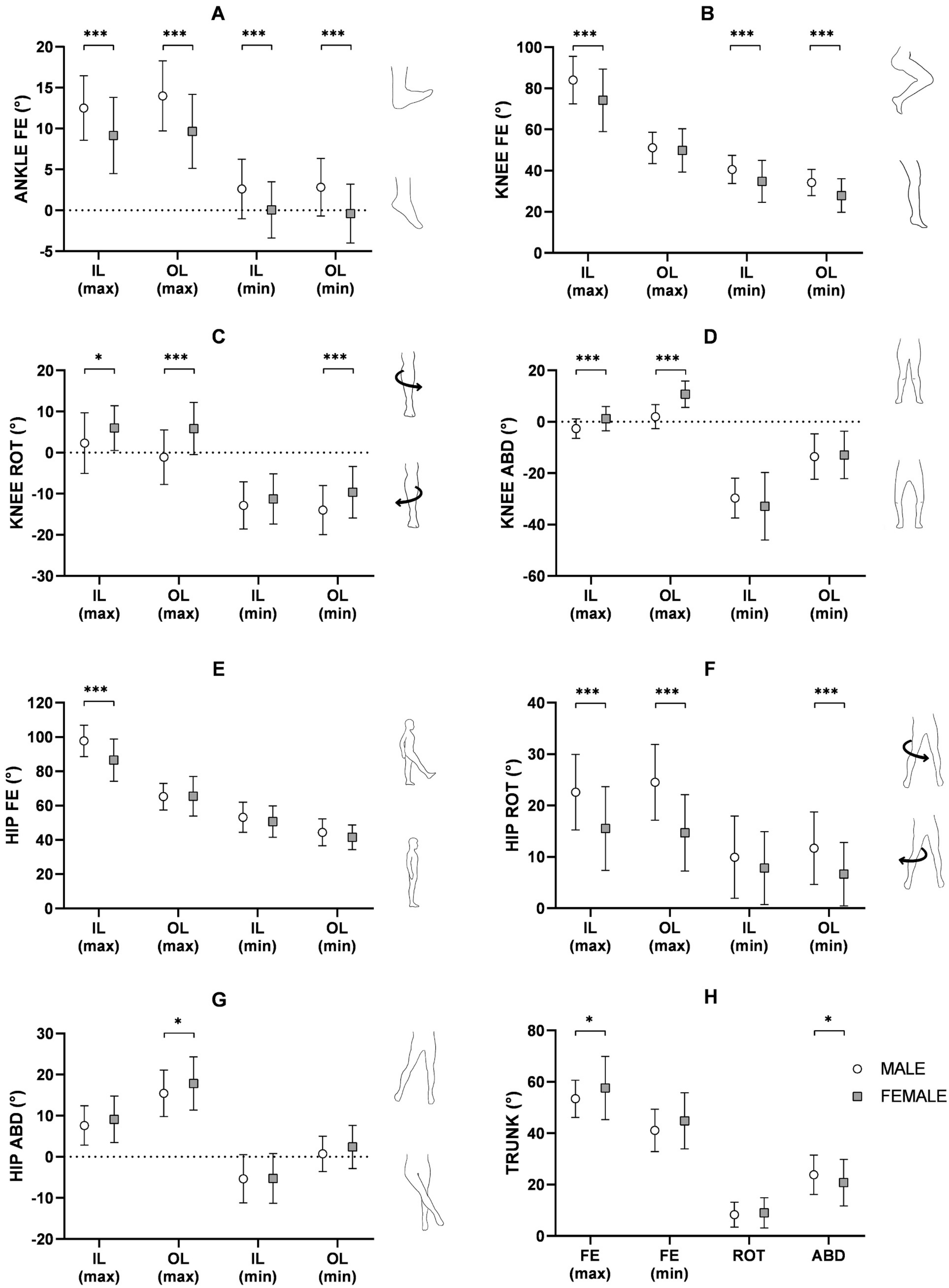

Fig. 2. Mean ± SD of maximum (max) and minimum (min) joint angle excursions for the inside (IL) and outside (OL) limb. (A) Ankle flexion–extension; (B) knee flexion; (C) knee rotation; (D) knee adduction–abduction; (E) hip flexion; (F) hip rotation; (G) hip abduction; (H) Maximum and minimum trunk flexion (FE), maximum trunk rotation (ROT), and maximum trunk abduction (ABD). Symbols indicate significant comparisons (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$).

leg. For EO, activation was between 10% and 30% of MVC on both sides and for both sexes, while ES showed higher activation, up to 60% of MVC in males and 50% in females, but with a high SD, especially in the female group. Differently, RF activation resulted in higher values in females compared to males in the first 11% of the turn cycle in the IL ($p = 0.005$, $d = 0.52$), while no differences were highlighted in OL. The muscular activation peak for RF was approximately 60% on both sides and in both sexes. The male group showed greater activation than the female group in the bilateral BF. For the IL, differences were observed throughout the entire turn cycle ($p < 0.001$, $d = 0.72$), peaking at 40% of MVC. In contrast, for the OL, differences were significant from the start through 87% of the turn cycle ($p < 0.001$, $d = 0.78$), peaking at 50% of MVC. Muscular activation profiles are shown in Fig. 3.

Total FF's peak differed in the IL ($p < 0.001$, $r = 0.46$), with females higher than their male counterparts, but not in the OL. SPM showed a higher value of total FF in the female group compared to males from 0 to 10% and 85% onward (both $p < 0.001$, $d = 0.68$) for the IL, while the OL differed only in the last 12% of the turn cycle ($p < 0.001$, $d = 0.70$). Moreover, females showed higher forefoot FF than males, especially in the last 22% of the turn cycle for the OL ($p < 0.001$, $d = 0.64$). In contrast, for the IL, forefoot FF was higher at 0–31%, 35–51%, and 70% to the end of the turn cycle (all $p < 0.001$, $d = 0.68$, $d = 0.49$, and $d = 0.67$, respectively). Conversely, rearfoot FF was higher in the male group than female counterparts from 60 to 83% of the turn cycle in the IL ($p < 0.001$, $d = 0.71$) and from 19 to 83% in the OL ($p < 0.001$, $d = 0.71$). Fig. 4 shows these differences.

4. Discussion

Our study examined the biomechanical differences between male and female recreational alpine skiers during a series of turns. The results revealed significant sex differences in kinematics and muscle activation patterns, suggesting that male and female skiers employ distinct movement strategies to complete the turning task. With respect to our specific hypotheses, the first one of greater DKV in female skiers was supported by the data, while the second of greater RF activation was partially supported, with differences observed in the IL but not in the OL.

Our findings show greater knee and ankle flexion in males than in females during skiing, which is consistent with previous studies of sex-based differences in lower-limb joint strategies during dynamic sport tasks (Decker et al., 2003; Pappas et al., 2007). Greater joint flexion in males suggests a more compliant joint strategy, allowing better dissipation of forces through increased joint excursion during the turn. Conversely, the tendency for female skiers to maintain a less-flexed knee position has been identified as a crucial risk factor for ACL injuries (Hanimann et al., 2025). This behavior may result from a combination of neuromuscular and structural differences that reduce the efficiency of female skiers' musculature in managing the deceleration and redirection forces characteristic of skiing turns. Our observation of DKV among female skiers supports our first specific hypothesis. As DKV is the most cited non-contact injury mechanism for ACL tears (Hewett et al., 2005; Jordan et al., 2017), this finding is valuable for trainers and practitioners. Consistent with the distinct movement strategies suggested by our results, the kinematic differences observed at the hip further characterize the sex-specific motor patterns identified in this study. Our data revealed that males exhibited significantly greater hip internal rotation and less hip abduction compared to females. At first glance, this "hip-in" pattern (adducted and internally rotated) appears to replicate the components of dynamic valgus at the proximal end of the kinematic chain. This specific combination of hip adduction and internal rotation has been extensively linked in the literature to increased knee valgus load and, consequently, to an elevated risk of ACL injury (Powers, 2010). However, in the context of alpine skiing, this movement pattern is not necessarily indicative of a neuromuscular deficit but may instead reflect technique specificity. Successful carving turns require the skier to move their center of mass inside the turn by actively using hip adduction. Simultaneously, active hip internal rotation is a primary strategy for steering the femur, which directs the knee and ski into the new turn (Müller and Schwameder, 2003). Therefore, these findings may indicate that the greater hip adduction and internal rotation observed in males represents a performance-oriented, "hip-dominated" steering strategy. This strategy aligns with a greater trunk inclination, indicating a "top-down" skiing approach in which the hip and trunk are used to move the pelvis inward. This differs from the "knee-dominated" pattern seen in the female cohort, whose strategy appears to rely more on a "bottom-up" mechanism, using the ankle-knee axis of the outer leg to generate ski inclination and complete the turn.

The differences in muscle activation patterns between the sexes provide relevant insights into sex-specific movement strategies during alpine skiing turns. With respect to the second specific hypothesis,

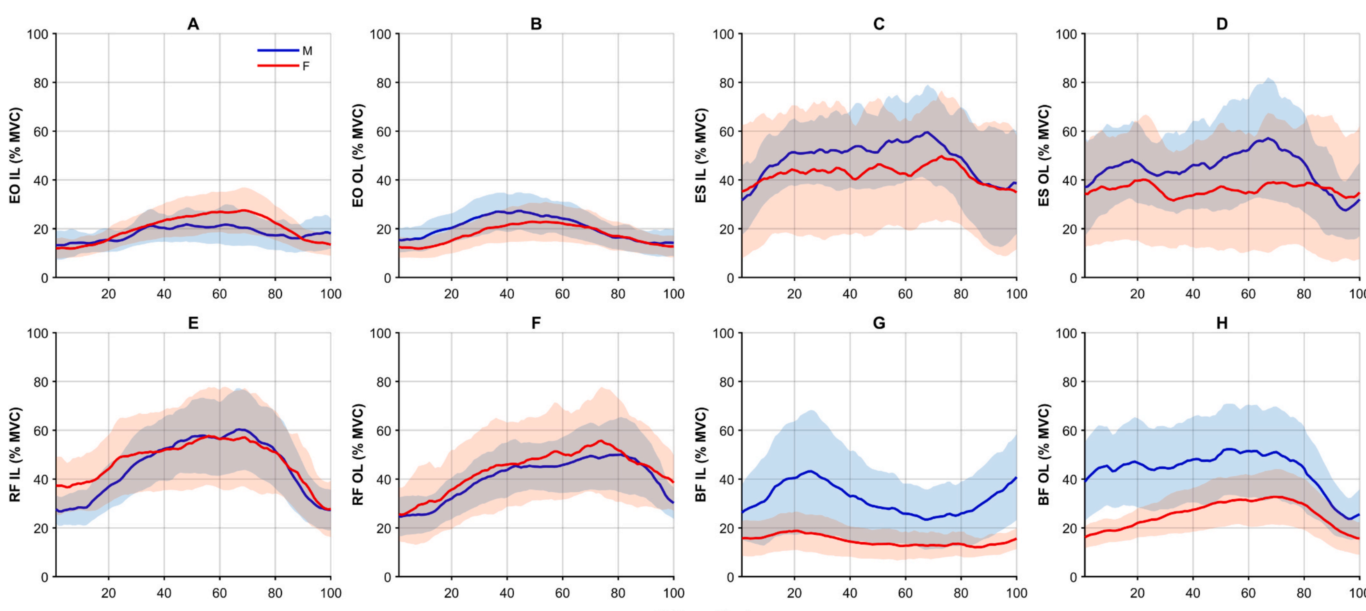

Fig. 3. Mean curves ± SD of EMG profiles across the turn cycle. Each subplot corresponds to a specific muscle and condition as indicated: A-B inside and outside external oblique (EO), C–D inside and outside extensor spinae (ES), E–F inside and outside rectus femoris (RF), G–H inside and outside biceps femoris (BF).

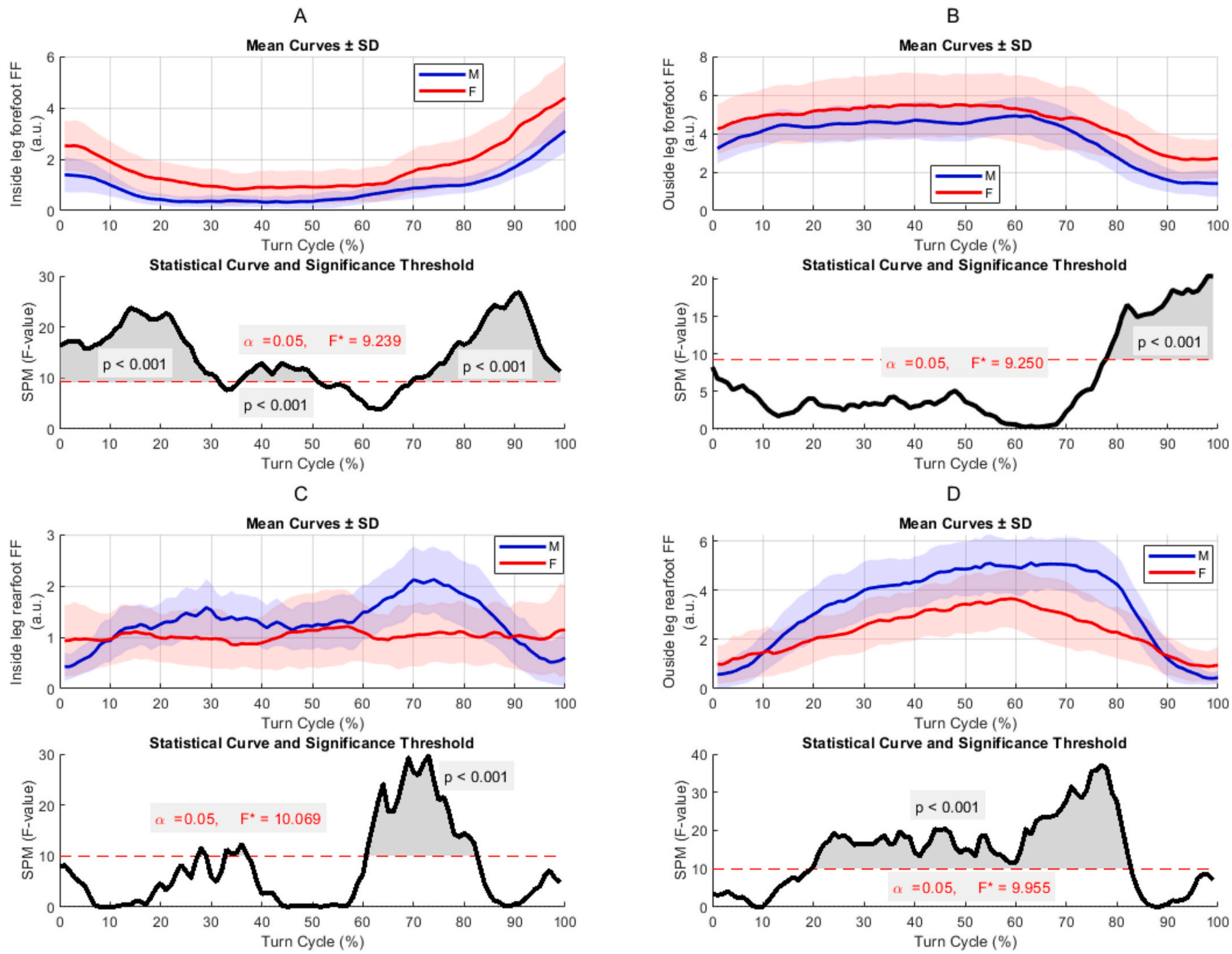

Fig. 4. Mean curves ± SD (top) and SPM statistic curves (bottom) for (A) forefoot force inside leg, (B) forefoot force outside leg, (C) rearfoot force inside leg, and (D) rearfoot force outside leg.

greater RF activation was observed in the IL of female skiers compared to males, but not in the OL. This is consistent with the study by Kröll and colleagues (2010), which investigated recreational female skiers and found greater RF activation in the IL than in the OL, suggesting that female skiers tend to rely more on the IL. In addition, we found lower BF activation in females than in males throughout most of the turn cycle. This combination of greater quadriceps dominance and reduced hamstring activation is consistent with the theory that an unbalanced hamstring-to-quadriceps strength ratio increases the risk of ACL injury in females (Zebis et al., 2009). The greater BF activation observed in males may provide greater dynamic knee stability during turns, as hamstring muscles act as dynamic stabilizers by limiting anterior tibial translation (Bencke et al., 2018). While males may rely on a balanced co-activation of quadriceps and hamstrings, the female's activation pattern, characterized by greater reliance on the rectus femoris, may increase mechanical stress on the knee. Our data suggest that this mechanism may be relevant in alpine skiing. These findings highlight the potential value of sex-specific training programs targeting knee stabilizing musculature and hamstring-quadriceps co-activation.

The kinetic results show that females exert a higher total and forefoot force when normalized to the subject's body weight, especially in the final phase of the turn, while males apply a greater rearfoot force. This finding is particularly interesting, given that the literature suggests that females exert peak forces up to 140% higher than males when landing from a jump (Pappas et al., 2007). Although our study does not focus on jumping, these exploratory findings suggest that the combination of higher forefoot loading and the valgus knee position observed in female skiers may increase knee joint loading, a pattern that warrants further investigation regarding knee injury mechanisms in recreational alpine skiers.

In addition to intrinsic biomechanical factors, our results and the literature suggest that equipment can play a fundamental role in preventing ACL injuries. Given the significant biomechanical differences, these findings suggest that ski equipment design, particularly ski boots, may benefit from greater consideration of female-specific morphology. Traditional ski boots have been designed based on male anatomical parameters, often failing to accommodate women's unique physiological characteristics. Specifically, the lower, more posterior calf muscle and the higher, forward-oriented tibial plateau in women (Hashemi et al., 2008) can lead to improper boot fit and alignment. Our findings on increased knee valgus in female skiers suggest that boot design, specifically the canting adjustment, may be a relevant factor worth investigating in future research. Canting, the angle adjustment of the boot cuff relative to the ski, may influence knee alignment during skiing, and future studies could examine whether optimized canting adjustments could help reduce knee valgus in female recreational skiers. This, together with ski-binding adjustment as proposed by Posch et al. (2025), represents a promising avenue for future research to improve the quality of recreational alpine skiing equipment for female skiers.

4.1. Limitation

While this study offers valuable insights, it is not without limitations. Although small sample sizes are a well-documented characteristic of on-field alpine skiing biomechanics research — with a recent scoping review reporting an average of 7.5 ± 5.5 participants across IMU-based kinematic studies (Presicci et al., 2025) — the present sample of 16 participants may still limit the generalizability of the findings, and replication in larger cohorts is warranted. Although participants were matched for technical skill level, the female group had a considerably lower mean age than the male group, which may have influenced some of the observed biomechanical differences. Differences in height and body mass between groups reflect expected anthropometric dimorphism between sexes; however, their potential contribution to the observed kinematic and kinetic differences cannot be excluded. The study's focus on recreational skiers, while addressing a notable gap in the literature, may mean the findings are not directly applicable to elite-level athletes (and vice versa). Future research should aim to replicate these findings with a larger, more age-matched and anthropometrically homogeneous cohort and explore how these biomechanical differences manifest across various skill levels and under different skiing conditions.

5. Conclusions

This study provides quantitative evidence that recreational alpine skiing exhibits distinct sex-specific biomechanical profiles, suggesting that injury-prevention strategies may benefit from sex-specific considerations. The data indicate that female skiers tend to adopt a kinematic and neuromuscular strategy characterized by DKV and quadriceps dominance, which has been associated with increased knee joint loading in the sports biomechanics literature. This movement pattern is consistent with known risk factors for non-contact ACL injury, though prospective research is needed to confirm a direct link. These findings highlight two promising directions for future research and practice. First, sex-specific neuromuscular training programs targeting posterior chain engagement and hamstring-quadriceps co-activation may represent a valuable avenue for injury prevention in female recreational skiers. Second, ski boot design may benefit from greater consideration of female-specific anatomical and biomechanical characteristics, particularly in lower-limb alignment.

Conflicts of interest / commercial interests

The authors indicate that we have no conflicts of interest to declare. We have no financial or other interest in any commercial product or distributor of a product mentioned in this manuscript.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used Claude (Anthropic) to assist with language editing and scientific writing refinement. The author(s) reviewed and edited the output as needed and take full responsibility for the content of the published article.

Author contribution

GCC, LB, and MB conceived the study design and the experimental setup. GCC, IC, PT, VV, MM, and LB performed the data collection. GCC and IC performed the data analysis, in collaboration with PT and VV and under the supervision of the remaining co-authors. GCC wrote the original draft of the manuscript; all authors reviewed, edited, and approved the final version.

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Originality declaration

We declare that this manuscript has not been published elsewhere, is not currently being considered for publication elsewhere, and the research reported will not be submitted for publication elsewhere until a final decision has been made as to its acceptability by the Journal.

Ethical guidelines

This research followed all necessary Ethical Guidelines. The local ethics committee of the University of Verona approved the study protocol (Project CARP #41/2024) and ensured compliance with the Declaration of Helsinki. Before data collection, all participants were adequately informed about the experimental procedures and gave their written informed consent for the measurements.

CRediT authorship contribution statement

Giorgia Celeste Cuniberti: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Isacco Costa:** Writing – review & editing, Investigation, Data curation. **Peppino Tropea:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Valeria Vella:** Writing – review & editing, Methodology, Investigation. **Michele Mattivi:** Writing – review & editing, Investigation. **Michele Botteon:** Writing – review & editing, Resources, Funding acquisition. **Federico Schena:** Writing – review & editing, Supervision, Funding acquisition. **Barbara Pellegrini:** Writing – review & editing, Supervision. **Lorenzo Bortolan:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2026.113543.

References

Alejo, L.B., Gil-Cabrera, J., Montalvo-Pérez, A., Barranco-Gil, D., Hortal-Fondón, J., Navandar, A., 2021. Performance parameters in competitive alpine skiing disciplines of slalom, giant slalom and super-giant slalom. Int. J. Environ. Res. Public Health 18, 1–11. https://doi.org/10.3390/ijerph18052628.

Alhammoud, M., Girard, O., Hansen, C., Racinais, S., Meyer, F., Hautier, C.A., Morel, B., 2022. Repeated practice runs during on-snow training do not generate any measurable neuromuscular alterations in elite alpine skiers. Front. Sports Act. Living 4, 829195. https://doi.org/10.3389/fspor.2022.829195.

Alhammoud, M., Hansen, C., Meyer, F., Hautier, C., Morel, B., 2020. On-field ski kinematic according to leg and discipline in elite alpine skiers. Front. Sports Active Living 2. https://doi.org/10.3389/fspor.2020.00056.

Alhammoud, M., Morel, B., Hansen, C., Wilson, M., Mecca, R., Nael, E., Hautier, C., 2019. Discipline and sex differences in angle-specific isokinetic analysis in elite skiers. Int. J. Sports Med. 40, 317–330. https://doi.org/10.1055/a-0850-0016.

Ammerman, B., Richards, M., Davie, R., Pahapill, N., Sutton, K., 2024. Difference in injury risk between male and female alpine skiers. Review of the Literature. J Sports Med Ther 9, 011–014. https://doi.org/10.29328/journal.jsmt.1001075.

Bencke, J., Aagaard, P., Zebis, M.K., 2018. Muscle activation during ACL injury risk movements in young female athletes: a narrative review. Front. Physiol. 9, 445. https://doi.org/10.3389/fphys.2018.00445.

Bhatt, A.M., Lucido, M.F., Patton, C.D., Brown, E., Inclan, P.M., Pearle, A.D., 2025. Multiple intrinsic and extrinsic factors increase the risk of anterior cruciate ligament injury in skiers: a systematic review. Arthroscopy: the Journal of Arthroscopic & Related Surgery 41, 5453–5469.e1. https://doi.org/10.1016/j.arthro.2025.07.027.

Blanke, F., Kiapour, A.M., Haenle, M., Fischer, J., Majewski, M., Vogt;, S., Camathias, C., 2016. Risk of noncontact anterior cruciate ligament injuries is not associated with slope and concavity of the tibial plateau in recreational alpine skiers: a magnetic resonance imaging–based case-control study of 121 patients. Am. J. Sports Med. 44, 1508–1514. https://doi.org/10.1177/0363546516632332.

Decker, M.J., Torry, M.R., Wyland, D.J., Sterett, W.I., Richard Steadman, J., 2003. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. Clin. Biomech. 18, 662–669. https://doi.org/10.1016/S0268-0033(03)00090-1.

FISI (Federazione Italiana Sport Invernali), 2018. Sci Alpino: Testo Tecnico 2018. Milano: Co.Scu.Ma.

Ge Wu, Sorin Siegler, Paul Allard, Chris Kirtley, Alberto Leardini, Dieter Rosenbaum, Mike Whittle, Darryl D D'Lima, Luca Cristofolini, Hartmut Witte, Oskar Schmid, Ian Stokes, Standardization and Terminology Committee of the International Society of Biomechanics, 2002. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion-part I: ankle, hip, and spine. International Society of Biomechanics. Journal of Biomechanics 543–548.

Grood, E.S., Suntay, W.J., 1983. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J. Biomech. Eng. 105, 136–144. https://doi.org/10.1115/1.3138397.

Hanimann, J., Fitze, D.P., Koller, T., Schürmann, F., Fröhlich, S., Feuerriegel, G.C., Stern, C., Scherr, J., De Bruin, E.D., Sutter, R., Spörri, J., 2025. Traumatic knee injuries and career drop-outs in adolescent competitive alpine skiers aged 15–19: a longitudinal 4-year follow-up study examining rates, biomechanical injury risk factors and potential reasons for quitting. Ann. Med. 57, 2532118. https://doi.org/10.1080/07853890.2025.2532118.

Hermens, H.J., Freriks, B., Disselhorst-Klug, C., Rau, G., 2000. Development of recommendations for SEMG sensors and sensor placement procedures. J. Electromyogr. Kinesiol.

Hewett, T.E., Myer, G.D., Ford, K.R., Heidt, R.S., Colosimo, A.J., McLean, S.G., Van Den Bogert, A.J., Paterno, M.V., Succop, P., 2005. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am. J. Sports Med. 33, 492–501. https://doi.org/10.1177/0363546504269591.

Hu, Z., Zhang, Y., Dong, T., Dong, M., Kim, S., Kim, Y., 2023. Gender differences in neuromuscular control during the preparation phase of single-leg landing task in badminton. JCM 12, 3296. https://doi.org/10.3390/jcm12093296.

Jordan, M., Aagaard, P., Herzog, W., 2017. Anterior cruciate ligament injury/reinjury in alpine ski racing: a narrative review. OAJSM 8, 71–83. https://doi.org/10.2147/OAJSM.S106699.

Khou, S.B., Saki, F., Tahayori, B., 2024. Muscle activation in the lower limb muscles in individuals with dynamic knee valgus during single-leg and overhead squats: a meta-analysis study. BMC Musculoskelet. Disord. 25, 652. https://doi.org/10.1186/s12891-024-07759-6.

Klous, M., Müller, E., Schwameder, H., 2012. Three-dimensional knee joint loading in alpine skiing: a comparison between a carved and a skidded turn. J. Appl. Biomech.

Korpinen, M.M., Trieschock, D., Fields, J.B., Jagim, A.R., Almonroeder, T.G., Jones, M.T., 2025. Hamstring-to-quadriceps strength ratios in women team sport athletes: a systematic review. Strength & Conditioning Journal 47, 95–108. https://doi.org/10.1519/SSC.0000000000000867.

Kröll, J., Wakeling, J.M., Seifert, J.G., Müller, E., 2010. Quadriceps muscle function during recreational alpine skiing. Med. Sci. Sports Exerc. 42, 1545–1556. https://doi.org/10.1249/MSS.0b013e3181d299cf.

Martínez, A., Nakazato, K., Scheiber, P., Snyder, C., Stöggl, T., 2020. Comparison of the turn switch time points measured by portable force platforms and pressure insoles. Front. Sports Act. Living 2, 2. https://doi.org/10.3389/fspor.2020.00002.

Martínez, A., Snyder, C., Moore, S.R., Stöggl, T., 2021. A comprehensive comparison and validation of published methods to detect turn switch during alpine skiing. Sensors 21. https://doi.org/10.3390/s21072573.

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

Pappas, E., Sheikhzadeh, A., Hagins, M., Nordin, M., 2007. The effect of gender and fatigue on the biomechanics of bilateral landings from a jump: peak values. J. Sports Sci. Med. 6, 77–84.

Posch, M., Mohr, M., Burtscher, M., Greier, K., Scharbert, J., Ruedl, G., 2025. Impact of an elevated rear component of the ski binding on joint angles of the lower extremity and the center of mass in recreational skiers. J. Hum. Kinet. https://doi.org/10.5114/jhk/194305.

Powers, C.M., 2010. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. J. Orthop. Sports Phys. Ther. 40, 42–51. https://doi.org/10.2519/jospt.2010.3337.

Powers, C.M., Fisher, B., 2010. Mechanisms underlying ACL injury-prevention training: the brain-behavior relationship. J. Athl. Train. 45, 513–515. https://doi.org/10.4085/1062-6050-45.5.513.

Presicci, C., Ingegnosi, I., Dondero, P., Casadio, M., Pierella, C., 2025. IMU-based systems for skiing sports: a scoping review. IEEE Access 13, 152430–152451. https://doi.org/10.1109/ACCESS.2025.3604571.

Ruedl, G., Posch, M., Tecklenburg, K., Schranz, A., Faulhaber, M., Burtscher, M., 2023. Skill-specific differences in equipment-related risk factors for ACL injury in male and female recreational skiers. Orthop. J. Sports Med. 11. https://doi.org/10.1177/23259671231155841.

Shams, F., Hadadnezhad, M., Letafatkar, A., Hogg, J., 2022. Valgus control feedback and taping improves the effects of plyometric exercises in women with dynamic knee valgus. Sports Health: A Multidisciplinary Approach 14, 747–757. https://doi.org/10.1177/19417381211049805.

Shi, H., Jiang, Y., Ren, S., Hu, X., Huang, H., Ao, Y., 2020. Sex differences in the knee orthopaedic injury patterns among recreational alpine skiers. BMC Sports Sci. Med. Rehabil. 12, 74. https://doi.org/10.1186/s13102-020-00224-6.

Vera-Garcia, F.J., Moreside, J.M., McGill, S.M., 2010. MVC techniques to normalize trunk muscle EMG in healthy women. J. Electromyogr. Kinesiol. 20, 10–16. https://doi.org/10.1016/j.jelekin.2009.03.010.

Wagner, M., Liebensteiner, M., Dammerer, D., Neugebauer, J., Nardelli, P., Brunner, A., 2023. Incidence of alpine skiing and snowboarding injuries. Injury 54, 110830. https://doi.org/10.1016/j.injury.2023.05.061.

Zebis, M.K., Andersen, L.L., Bencke, J., Kjær, M., Aagaard, P., 2009. Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening. Am. J. Sports Med. 37, 1967–1973. https://doi.org/10.1177/0363546509335000.