Undergraduate Research Journal for the Human Sciences

Volume 18
Issue 2025 *2025*

Article 4

April 2025

# Impact of External Ankle Dorsiflexion Restriction on Sagittal Plane Kinematics and ACL Injury Risk in Big Mountain Skiers

Megan Bass
*Colorado College*, megan-bass@outlook.com

Kaelin Enga
*Colorado College*, kaelinenga22@gmail.com

Deirdre O'Sullivan
*Colorado College*, deosullivan02@gmail.com

*See next page for additional authors*



## Recommended Citation

Bass, Megan; Enga, Kaelin; O'Sullivan, Deirdre; O'Sullivan, Dori; and Murphy, Eryn (2025) "Impact of External Ankle Dorsiflexion Restriction on Sagittal Plane Kinematics and ACL Injury Risk in Big Mountain Skiers," *Undergraduate Research Journal for the Human Sciences*: Vol. 18: Iss. 2025.

# Impact of External Ankle Dorsiflexion Restriction on Sagittal Plane Kinematics and ACL Injury Risk in Big Mountain Skiers


## Authors

Megan Bass, Kaelin Enga, Deirdre O'Sullivan, Dori O'Sullivan, and Eryn Murphy

# Impact of External Ankle Dorsiflexion Restriction on Sagittal Plane Kinematics and ACL Injury Risk in Big Mountain Skiers

## Abstract

**Introduction.** Big mountain skiing involves frequent impacts on extreme terrain and stiff boots that alter lower extremity joint kinematics consistent with ACL injury mechanisms. Back-weighted sagittal loading patterns identified in Alpine skiing, such as boot-induced anterior drawer of the tibia, remain unstudied in big mountain skiing. **Purpose**. This study characterizes the effect of ankle dorsiflexion restriction induced by big mountain ski boots on lower extremity sagittal joint kinematics in the context of known ACL injury mechanics. **Methods.** Participants completed five isometric squats under two conditions: restricted and unrestricted ankle dorsiflexion. Squat trials simulated a skier's stance. Two-way ANOVA and paired t-tests compared restricted and unrestricted conditions. **Results.** Significant differences in ankle dorsiflexion and knee flexion angles were observed between conditions. **Conclusion.** These results indicate restrictive ski boots may alter sagittal plane kinematics in patterns consistent with ACL injury mechanisms in big mountain skiing.

*Key words:* skiing; ACL injury risk; ankle dorsiflexion restriction; sagittal plane

## Introduction

The Freeride World Tour defines big mountain skiing as "skiers and snowboarders choosing impossible-looking lines through cornices and cliff-faces and nasty couloirs" (*FWT – Freeride World Tour – Home of Freeride*, n.d.). Freeride competitions involve high-intensity impacts and drop landings on steep, ungroomed terrain, increasing risk of injuries. Expert skiers, such as big mountain skiers, typically choose a stiff ski boot (Böhm & Senner, 2008) with a higher "flex index," which measures boot resistance to forward flexion (Petrone et al., 2013). Stiffer flexural behaviors provide enhanced energy transfer by reducing energy dissipation during flexion and rebound, which describes the dynamic behavior of skis as they bend and return to their original shape during skiing (Hébert-Losier et al., 2014). This heightened control and increased responsiveness of the ski improves performance and reduces risk of ankle and tibial fractures (Lann Vel Lace & Błażkiewicz, 2021) but may increase risk of knee-ligament injury (Fong et al., 2011, Petrone et al., 2013). The bias toward stiffer boots in modern ski boot design has led to a nuanced balance between performance and safety.

In skiing disciplines, restricted ankle dorsiflexion range of motion (RADROM), as observed in stiff ski boot wear (Wilson et al., 2021), is associated with distinct loading patterns consistent with anterior cruciate ligament (ACL) injuries (Fong et al., 2011; Hagins et al., 2007). ACL injuries are the most common knee traumas in recreational Alpine skiers, representing 15–21% of all knee injuries in adult skiers of both sexes (Posch et al., 2021). This study sought to explore the impacts of RADROM induced by ski boots in the context of sagittal kinematics associated with ACL injury in big mountain skiers.

In physically active individuals, squatting tasks, RADROM is associated with decreased knee flexion, increased ground reaction forces (GRFs), and consequent greater valgus knee displacement, during squatting tasks, consistent with increased risk of ACL injury (Fong et al., 2011). Notably, these factors are further exacerbated in landing tasks as GRFs are greater (Fong et al., 2011; Hagins et al., 2007). These studies suggest RADROM corresponds with increased load on the knee due to the proximal transfer of GRFs (Fong et al., 2011; Hagins et al., 2007) and decreased shock absorption at the ankle (Shimokochi et al., 2013). In an investigation of the impact of ski boot ankle restriction on postural control, Wilson et al. suggests that kinetic loads are transferred proximally through the boot cuff to the tibia rather than absorbed at the ankle (Wilson et al., 2021). Thus, stiff ski boots that decrease ankle dorsiflexion ROM likely put skiers at higher risk of ACL injuries.

Ski boots restrict ankle ROM in frontal and sagittal planes (Lann Vel Lace & Błażkiewicz, 2021; Tchórzewski et al., 2013), reducing inversion and eversion of the ankle (Wilson et al., 2021) and forcing the tibiotalar joint into a dorsiflexed position (Böhm & Senner, 2008; Lann Vel Lace & Błażkiewicz, 2021). While this may aid in lateral balance, RADROM in ski boots reduces stability in the sagittal plane across the lower extremity (Tchórzewski et al., 2013), increasing loads on the knee and consequent ACL injury risk (Fong et al., 2011; Hagins et al., 2007; Wilson et al., 2021).

Frontal and sagittal plane mechanisms of ACL injury are well understood in Alpine skiing (Bere et al., 2011); however, these mechanisms are less investigated in the sub-discipline of big mountain skiing, despite the relevance of sagittal plane injury mechanisms in other Alpine disciplines (Bere et al., 2011). In an inquiry of footage from the International Ski Federation Injury Surveillance System and known ACL injury occurrences in World Cup downhill racers, Bere et al. (2011) observed three common mechanisms of injury: slip-catch, dynamic snowplow, and back-weighted landings. The slip-catch and dynamic snowplow mechanisms, colloquially known as "phantom foot" injuries, are primarily frontal plane mechanisms of injury that involve valgus displacement and internal rotation of the knee. Back-weighted landing mechanisms, however, occur within the sagittal plane; Bere et al. suggests loading mechanisms that combine tibiofemoral compression, quadriceps anterior drawer, and boot-induced anterior drawer (BIAD) of the tibia. ACL injuries caused by back-weighted landings, specifically the BIAD loading mechanism, may occur as a result of the stiff rear compartments of ski boots propelling the tibia forward as the skier's weight shifts posteriorly, causing the ACL to tear (Bere et al., 2011).

While sagittal plane mechanisms of injury have been identified and analyzed in other Alpine disciplines (Bere et al., 2011), they have yet to be explored in big mountain skiing. Boots commonly used in big mountain skiing are often suitable for other alpine disciplines; however, the nature of big mountain skiing, with its emphasis on jumping and navigating unpredictable terrain, can accentuate loading patterns observed in other disciplines (Bere et al., 2011). Given these loading patterns, the role of RADROM due to ski boot wear as it pertains to injury risk remains a relevant issue in big mountain skiing. With research on big mountain skiing and consequent ACL injury in its infancy, this study aims to understand the impact of ankle restriction induced by ski boots on lower extremity sagittal joint kinematics in big mountain skiers in a laboratory setting.

## Methods

*Participants.* Following approval from the Institutional Review Board, 18 participants (n=6 females, 19-22 years) were recruited from a college campus. Participants were recruited based on active participation in freeride competitions and extreme skiing, defined as skiing that involves steep descents on extreme, mountainous terrain, consistent with the big mountain skiing discipline. Exclusion criteria included history of ACL, medial cruciate ligament, or other knee injury, lower extremity injury in the last 6 months, or lack of freeride skiing participation. Concurrent participation in other disciplines was permissible. Each participant completed testing in their personal ski boots used for big mountain skiing.

*Segment marking.* After participants signed informed consent and photo release documents, intake procedures including identification of dominant leg, measurement of segment lengths, and measurement of active non-weight bearing ankle dorsiflexion were gathered. The dominant leg was defined as the leg that was the favored downhill ski while resting on an incline; all subsequent measurements were conducted on the dominant leg and unshod (Fong et al., 2011).

Four markers were placed on the dominant leg at the iliac crest of the pelvis, greater trochanter of the femur, lateral tibiofemoral joint space, and the lateral malleolus of the fibula (Della Croce et al., 1999). These landmarks were palpated on each participant and marked for motion capture technology (Della Croce et al., 1999). Markers were also placed on participants' ski boots at the approximate lateral malleolus of the fibula and distal end of the fifth metatarsal. Segment lengths (cm) were measured as follows: thigh, greater trochanter of the femur to lateral tibiofemoral joint space; shank, lateral tibiofemoral joint space to lateral malleolus of the fibula; total leg length, iliac crest of the pelvis to the floor, crossing the lateral malleolus.

*Range of motion*. Active non-weight bearing ankle dorsiflexion was measured with participants in a supine, subtalar neutral position, with their dominant foot placed flat against a wall, ankle at 90 degrees (this is consistent with 0 degrees dorsiflexion, or a neutral position), and knee fully extended (Carroll et al., 2021). Participants were directed to perform maximal active ankle dorsiflexion, with dorsiflexion recorded as the angle between the shank and the fifth metatarsal of the foot such that the edge of the goniometer sat in line with the head of the fifth metatarsal (Figure 1; Holmberg et al., 2005). Dorsiflexion was measured with a manual goniometer (Carroll et al., 2021).

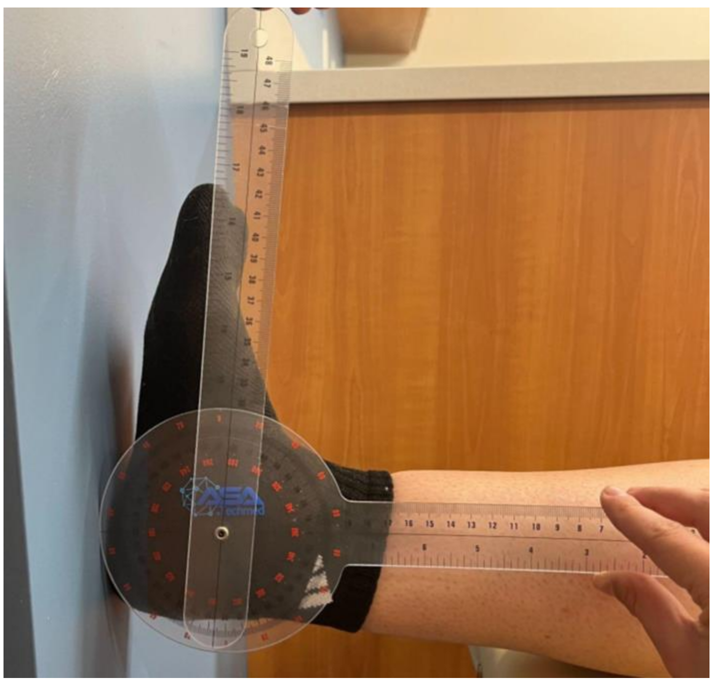

**Figure 1. Goniometric measurement of active non-weight bearing ankle dorsiflexion.**

*Testing conditions.* Participants were asked to complete one set of five isometric squats (Blackburn & Norcross, 2014) under two testing conditions: restricted ankle dorsiflexion (RAD) and unrestricted ankle dorsiflexion (UAD), which were completed in ski boots and unshod, respectively. The order of conditions was counterbalanced across participants. For restricted conditions, participants were asked to bring their personal ski boots and adjust the bindings as they would for big mountain skiing. Brand (Appendix A) and flex index (Table 1) of participant boots were recorded.

Prior to all squat trials, participants were instructed to stand in a comfortable, neutral stance; this was the position they were cued to return to between isometric squat trials. Additionally, in restricted conditions, participants were asked to maximally dorsiflex by leaning anteriorly into their boots to determine dorsiflexion allowed (booted maximal ankle dorsiflexion).

Under each condition, every squat was held for 15 seconds with a 5-second rest period between each repetition (Blackburn & Norcross, 2014). During the 5-second rest period, participants were instructed to return to their comfortable, neutral stance. In both RAD and UAD conditions, participants were cued to assume an approximation of a skier's squat with their ankles dorsiflexed, knees flexed forward, and hips flexed. Participants were additionally cued to recreate the stance they would assume while approaching steep terrain and to flex elbows at a 90-degree angle with arms tucked in to their side.

*Joint Angles.* Joint angles were measured at the tenth second of repetitions two, three, and four to account for familiarization and fatigue; sagittal plane joint angles of the ankles, knees, and hips of these three trials were averaged. Ankle dorsiflexion, knee flexion, and hip flexion angles were measured about the lateral malleolus of the fibula, lateral tibiofemoral joint space, and greater trochanter of the femur, respectively (Della Croce et al., 1999). Ankle dorsiflexion was measured as the angle about the lateral malleolus of the fibula, extending to the lateral tibiofemoral joint space marker and the distal end of the fifth metatarsal. Full extension of the knee was defined at 0 degrees. Full extension of the hip was defined at 180 degrees (Figure 2).

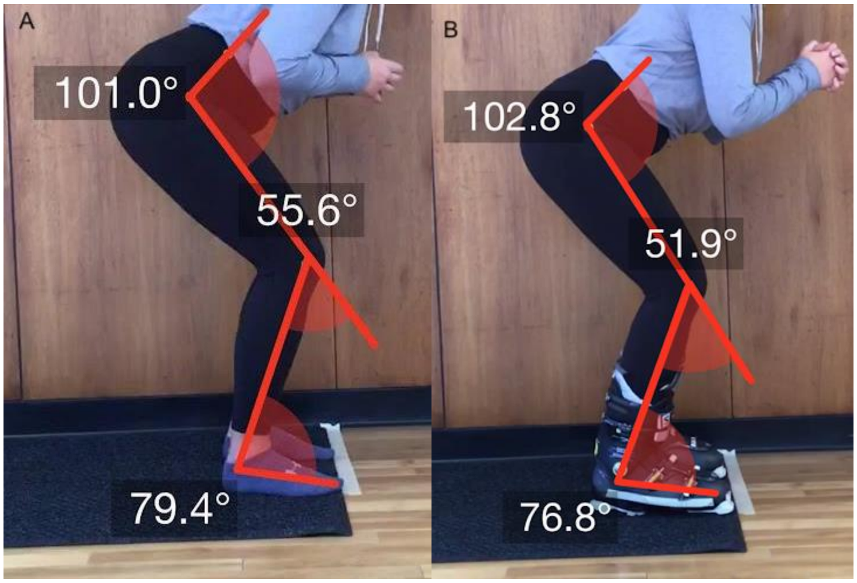


**Figure 2. Joint angle measurements during a simulated skier's squat.** Joint angles were measured as follows: ankle dorsiflexion was defined by the angle between the distal end of the fifth metatarsal and lateral tibiofemoral joint space, around the lateral malleolus of the fibula. Knee flexion was defined by the angle between the lateral malleolus of the fibula and greater trochanter of the femur, around the anterolateral tibiofemoral joint space. Hip flexion was defined by the angle between the iliac crest of the pelvis and the lateral tibiofemoral joint space, around the greater trochanter of the femur. **A.** typical UAD condition **B.** typical RAD condition.

*Instrumentation.* All joint angles were captured and analyzed using Dartfish motion capture software (Dartfish, Fribourg, Switzerland). The camera (iPad 10th Generation, Rear-facing Camera, 60fps) was placed in the sagittal plane, 290 cm away from participants and 75 cm off the ground. Participants stood with their dominant leg facing the camera (Norris & Olson, 2011).

*Analysis.* Collected data were preliminarily evaluated for measures of central tendency in Microsoft Excel (Microsoft, Redmond, WA). Ankle dorsiflexion, knee flexion, and hip flexion angles from squat trials two, three, and four from each condition were averaged for further analysis. All trials and participants were included in the analysis.

A two-way ANOVA was performed to evaluate the relationship across joints between RAD and UAD conditions. Average angles from RAD and UAD trials for each participant were compared using a two-tailed paired t-test. A Bonferroni correction was applied as a multiple-comparison correction to determine statistical significance, such that $p < 0.017$ would be deemed statistically significant. Cohen's *d* calculations were performed to report effect size (Lakens, 2013). Statistical testing was conducted in GraphPad Prism (GraphPad Prism, Boston, MA).

## Results

18 big mountain skiers were recruited (n=6 female) and completed testing. The average age of participants was 20.50 ± 0.92 years with an average of 17.44 ± 2.33 years of skiing experience. The average height of participants was 171.10 ± 8.13 cm and average weight was 70.18 ± 8.70 kg. Five participants reported left-leg dominance. Average active non-weight bearing ankle dorsiflexion was 82.89 ± 2.54 degrees (Table 1).

A two-way ANOVA demonstrated a statistically significant interaction effect of ankle restriction on sagittal plane kinematics, $F(2,102) = 3.085$, $p = 0.012$, (Figure 4). Significant main effects of ankle restriction at the ankle and knee were present. Participants displayed greater ankle dorsiflexion in UAD compared to RAD (61.41 ± 5.83 degrees and 68.24 ± 3.23 degrees UAD and RAD, respectively, $p < 0.017$, $d = 1.4$) and knee flexion angles were significantly greater in UAD compared to RAD (58.47 ± 9.87 degrees and 46.93 ± 8.35 degrees UAD and RAD, respectively, $p < 0.017$, $d = 1.3$). There were no significant differences found in hip flexion between conditions (129.45 ± 20.64 degrees and 121.63 ± 21.36 degrees UAD and RAD, respectively, $p = 0.0456$, $d = 0.4$; Figure 3).

Post-hoc regression testing of nominal boot flex and intake active dorsiflexion, as well as booted maximal dorsiflexion revealed no significant relationships between variables ($R^2 = 0.151$, $p = 0.11$, and $R^2 = 0.03$, $p = 0.48$ respectively). Post-hoc testing revealed no significant difference between male and female hip flexion angles in RAD (133.36 ± 17.28 and 121.6 ± 26.11 degrees male and female respectively, $p = 0.353$) and UAD conditions (126.06 ± 20.03 and 112.8 ± 22.99 degrees male and female respectively, $p = 0.260$).

**Table 1**

*Demographic information of 18 participants included in the study*

| | Average | Standard Deviation |
|---|---|---|
| Age (years) | 20.50 | 0.92 |
| Height (cm) | 171.10 | 8.13 |
| Weight (kg) | 70.18 | 8.70 |
| Ski experience (years) | 17.44 | 2.33 |
| Boot flex (degrees) | 119.41 | 16.29 |
| Total leg length (cm) | 105.84 | 4.96 |
| Thigh length (cm) | 45.50 | 3.29 |
| Shank length (cm) | 41.64 | 2.67 |
| Active ankle dorsiflexion (degrees) | 82.89 | 2.54 |
| Maximal booted dorsiflexion (degrees) | 61.81 | 3.76 |

**Table 2**

*Joint angle measurements from isometric squat trials*

| | UAD | RAD | ***p* value** | **Cohen's *d*** |
|---|---|---|---|---|
| Ankle Dorsiflexion (degrees) | 61.41 ± 5.83 | 68.24 ± 3.23* | 0.0015 | 1.45 |
| Knee Flexion (degrees) | 58.47 ± 9.87 | 46.93 ± 8.35* | <0.0001 | 1.26 |
| Hip Flexion (degrees) | 129.45 ± 20.64 | 121.63 ± 21.36 | 0.046 | 0.37 |

*Note.* measurements include average ankle dorsiflexion, knee flexion, and hip flexion in unrestricted (UAD) and restricted ankle dorsiflexion (RAD) conditions. n=18. *Indicates a significant difference from UAD, $p<0.017$.

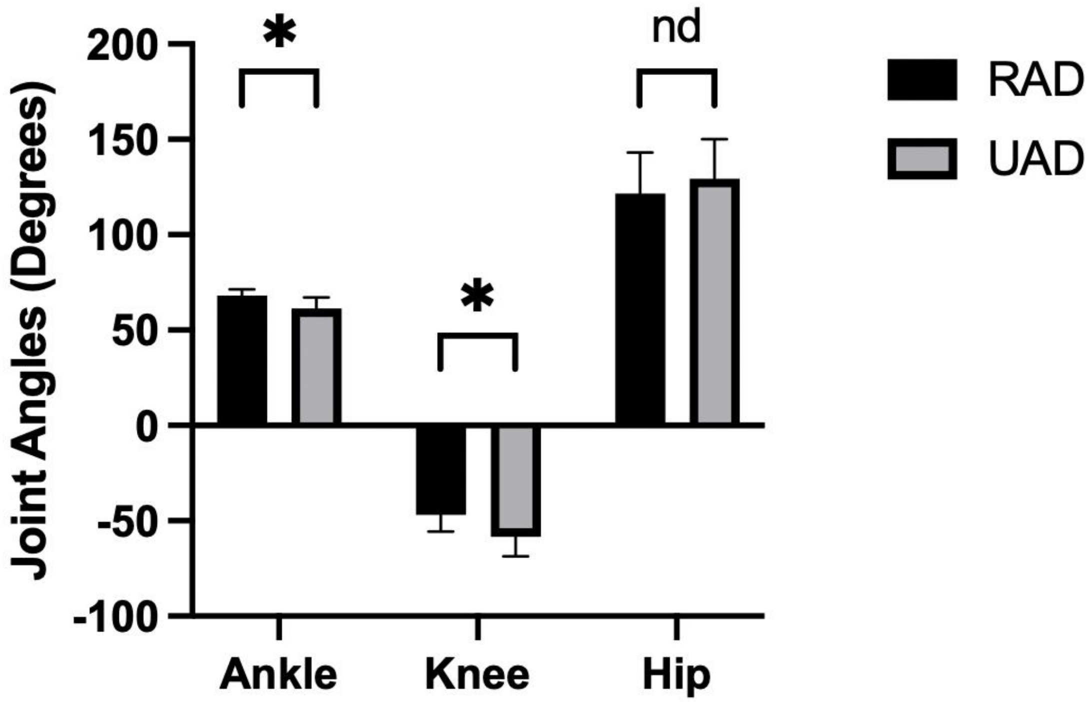


**Figure 3. Statistically significant differences between average ankle and knee flexion during isometric squats under RAD and UAD conditions.** Across all joints, more positive values represent greater extension while more negative values represent greater flexion. *Indicates significant difference, $p<0.017$. Differences where $p \geq 0.017$ are marked as no difference (nd).

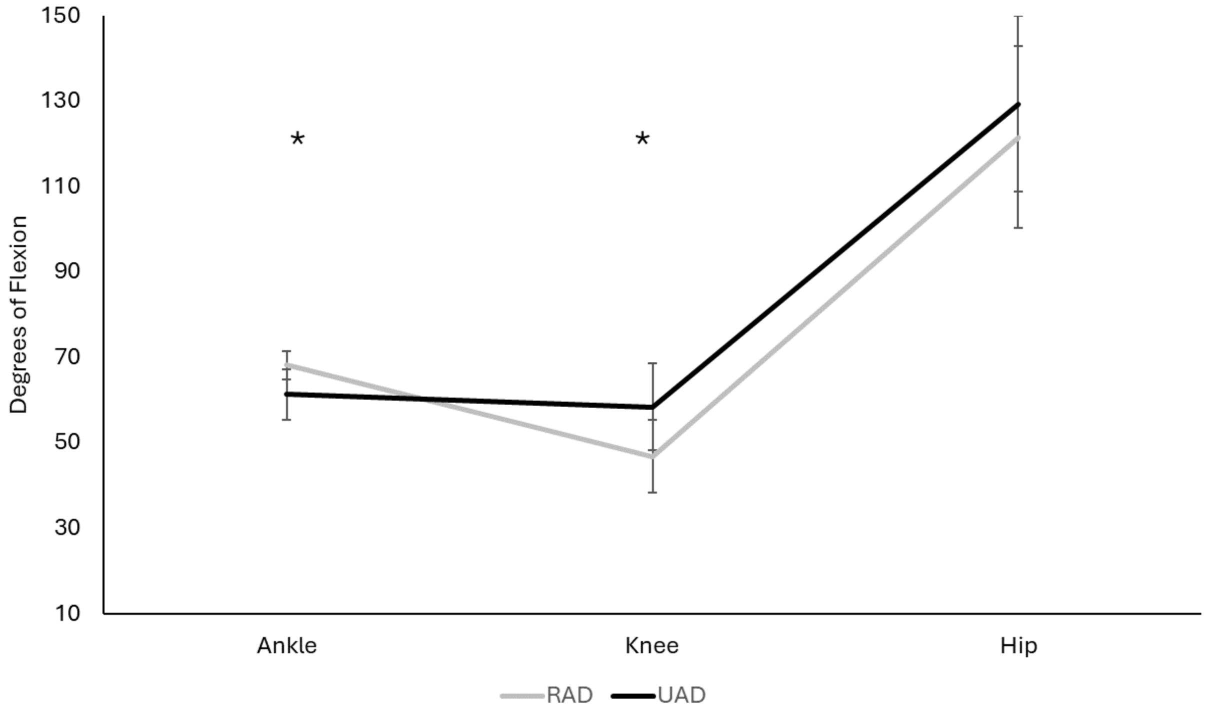


**Figure 4. Significant interaction effects of ankle restriction on sagittal plane lower extremity joint kinematics.** Results of the two-way ANOVA demonstrating significant interaction effects of ankle restriction on sagittal plane kinematics, $F(2,102) = 3.085$, $p = 0.012$. Significant main effects were observed at the ankle and knee, $p = 0.0015$ and $p < 0.0001$ respectively.

## Discussion

This study explored the impacts of restricted and unrestricted ankle dorsiflexion on lower extremity sagittal plane mechanics during isometric squats in big mountain skiers. Due to its extreme nature, big mountain skiing presents a high risk of ACL injury; however, relevant sagittal plane loading mechanisms, such as back-weighted landings and subsequent BIAD injury mechanisms (Bere et al., 2011), remain unstudied in this skiing discipline. Consistent with our inclusion criteria, our sample represented expert, extreme skiers. The average age of participants was 20.50 ± 0.92 years with an average of 17.44 ± 2.33 years of skiing experience; most participants had been skiing for more than 15 years (n=17). Results from this study have been considered in the context of ACL injury mechanisms.

Measurements of active non-weight bearing dorsiflexion measured upon intake were consistent with values previously identified in adults aged 18-45 years after accounting for differences in methodology (Carroll et al., 2021). Because our active non-weight bearing dorsiflexion fell within normal ranges and was therefore unrestricted by intrinsic factors, any restriction of dorsiflexion observed in RAD trials can likely be attributed to ski boot wear rather than confounding variables. Given that restricted ankle dorsiflexion is associated with increased loads on the knee during dynamic tasks (Fong et al., 2011) like high-impact events observed in big mountain skiing, quantifying the effects of externally restricted ankle dorsiflexion is critical to understanding ACL injury risk in this discipline.

Knee and hip joint measurements from this study were consistent with prior studies of skiing kinematics (Böhm & Senner, 2008; Holmberg et al., 2005; Yoneyama et al., 2000). The RAD knee flexion angles (46.93 ± 8.35 degrees) found in this study were similar to average knee angles identified during simulated skiing conditions (45.8 ± 8.9 degrees; Böhm & Senner, 2008) as well as outdoor skiing conditions (Yoneyama et al., 2000). Likewise, the UAD and RAD hip flexion angles (129.45 ± 20.64 degrees and 121.64 ± 21.36 degrees, UAD and RAD, respectively) in our study fell within the range reported by Holmberg et al. during pole plants of Nordic skiers (Holmberg et al., 2005). Despite this study occurring on a flat surface (due to laboratory limitations) in the absence of skis, these comparisons indicate our results are consistent with field skiing positions.

Our results also confirmed that the effects of external restricted ankle dorsiflexion are tangible far beyond the ankle (Wilson et al., 2021). Significant interactions across the ankle, knee, and hip were observed between RAD and UAD conditions, with significant main effect differences at the ankle and knee ($p$=0.0015 and $p$<0.0001 ankle and knee, respectively). It is important to recall that due to our methodology, a greater reported joint angle at the ankle and hip indicated lesser degrees of flexion about that joint. As previously discussed, RAD trials had less total dorsiflexion, and lesser consequent knee flexion. While hip differences were non-significant, RAD trials trended toward a more flexed position, as well. Conversely, under UAD conditions with no external ankle restriction, ankle dorsiflexion and knee flexion were greater, and hips were more extended. This significant interaction affirmed that ankle restriction results in compensatory kinematics at the knee that are consistent with risk of ACL injury mechanics (Almansoof et al., 2023). Readers should consider the relationship between intrinsic restrictions to dorsiflexion while in a flexed-knee position due to variations in the tension across the gastrocnemius compared to soleus while interpreting our results, although such contributions were not measured.

Statistically significant main effects with large effect sizes (Table 2; Lakens, 2013) in ankle and knee kinematics were present in this study. Specifically, we observed less ankle dorsiflexion in RAD versus UAD trials (68.24 ± 5.84 degrees and 61.41 ± 5.84 degrees RAD and UAD, respectively, $p<0.017$) and lesser knee flexion (greater knee extension) in the RAD condition (46.93 ± 8.35 degrees and 58.47 ± 9.87 degrees RAD and UAD, respectively, $p<0.017$). RADROM during drop landings is associated with decreased knee flexion and increased loads on the knee (Fong et al., 2011), patterns aligned with our observed comparison; these factors contribute to increased risk of knee ligament injury (Fong et al., 2011; Hagins et al., 2007). Consistent with these loading patterns (Fong et al., 2011; Hagins et al., 2007), the knee flexion angles measured in this study in RAD and UAD conditions (Table 2) fell within the range of 30-90 degrees of flexion under which the ACL is responsible for more than 80% of restraining forces of the knee (Mader et al., 2007). This suggests that the knee flexion angles observed were consistent with increased loads on the ACL and sagittal plane mechanisms of injury, such as BIAD in back-weighted landings (Bere et al., 2011). These loading mechanics are amplified in RAD conditions due to the external ankle restriction and consequent lesser knee flexion (Fong et al., 2011; Wilson et al., 2021).

While the ankle dorsiflexion and knee flexion angles in RAD corresponded with increased ACL loading (Fong et al., 2011) and back-weighted landing mechanisms of injury (Bere et al., 2011), the differences in hip flexion between conditions were not statistically significant ($p>0.017$). Cimino et al. found that greater extension of the hip paired with minimal contraction of the hamstrings often coincides with ACL injury occurrences in skiers (Cimino et al., 2010). While we cannot make claims about muscle activity in restricted and unrestricted conditions, our trends of greater hip flexion in RAD trials contrasted with Cimino et al.'s results of greater hip extension during ACL injury events. Our differences in hip flexion may be accounted for by the fact that our study utilized isometric squat trials rather than drop-landings or more dynamic movements (Cimino et al., 2010); the full range of kinematics observed in a back-weighted landing mechanism of injury, such as BIAD, may not manifest in static tasks.

While differences in joint kinematics associated with ski boot wear were identified in this study, several variables have yet to be explored in more dynamic, controlled settings. This study utilized isometric as opposed to plyometric squat tasks due to laboratory limitations and to lower the risk of injury posed to participants during testing; however, consistent with results from Fong (2011) and Hagins (2007), we would argue that our significant results found in isometric conditions would only be accentuated by a more dynamic and demanding task such as a plyometric landing (Fong et al., 2011; Hagins et al., 2007). In all, the assessment of isometric squat kinematics posed by this study provides relevant groundwork for future research in this field but leaves much to be explored in more dynamic conditions.

To investigate the lack of statistical significance in hip flexion angles observed in this study, we performed a post-hoc analysis. While our study did not explicitly explore differences between males and females in the sagittal or frontal planes, differences in factors including limb alignment, notch dimensions, and ligament laxity are well documented (Cimino et al., 2010; Evans et al., 2024; Viola et al., 1999). Furthermore, quadriceps dominance in females increases risk of ACL injury (Evans et al., 2024), a pattern consistent with back-weighted loading patterns including the BIAD injury mechanism (Bere et al., 2011; Cimino et al., 2010), and not explicitly measured in this study. While post-hoc analysis revealed no statistically significant relationship between sex and hip flexion, it could account for the large variance we observed in hip flexion. We hypothesize that a more dynamic task, such as a drop-landing, would require greater hip flexion to absorb landing forces, and may elucidate greater differences between sexes.

It is also important to consider the effect of temperature on the flexural behavior of ski boots. The laboratory was not temperature-controlled, and therefore boots may have behaved differently due to the temperature of the room; ski boots tend to be stiffer at lower temperatures, consistent with those found in field settings (Petrone et al., 2013, 2014). In this study, the temperature during testing fluctuated between 20°C and 25°C. This laboratory temperature may have resulted in less restriction of ankle dorsiflexion ROM than that which would be observed in a field setting. In contrast, Noé et al. found no significant difference in lower extremity kinematics in soft versus rigid ski boots; while they did not explicitly investigate temperature effects on boot rigidity and consequent kinematics, it does challenge whether we would have observed different results in a climate-controlled setting (Noé et al., 2020).

In an effort to improve external validity, participants were instructed to bring their preferred big mountain ski boots and adjust them as they would in the field, resulting in the representation of many different brands, flexes, and settings of boots in our data set. It is reasonable to assume maximal active dorsiflexion may influence boot preference and the flex of the boot may affect maximal booted dorsiflexion; however, in post-hoc testing, we found no significant linear relationship between nominal flex of ski boots and intake active dorsiflexion or booted maximal dorsiflexion. This may be explained by the lack of standardization in nominal flex across ski boot manufacturers, which may not accurately represent the actual flexural behavior (Petrone et al., 2013, 2014). As a result, we completed no further analysis on nominal boot flex, although future research with larger sample sizes may consider this as an avenue of study.

This research investigated the effects of ankle restriction induced by big mountain ski boots on sagittal plane lower extremity kinematics in a laboratory setting. Still, a great deal remains unknown about the mechanisms of ACL injury in the field, especially those occurring in the sagittal plane or muscle activation patterns. Further research on the impact of ankle dorsiflexion restriction should consider muscle activation patterns primarily of the quadricep and hamstring, as this could help define additional parameters of ACL injury risk in this population; consideration of differences between sexes could yield valuable information on sagittal plane injury risk as well. Furthermore, study of kinetic variables due to stiff ski boots, particularly the effects of ankle restriction on center of pressure during dynamic tasks, would help further define back-weighted loading mechanisms and BIAD injury mechanisms. Future studies should also consider differences in sagittal plane mechanisms of ACL injury related to ski length and while on sloped surfaces. These factors could introduce more variables impacting RADROM and bring lab setting trials on ski boots closer to real skiing scenarios. While there is room for this field of research to grow, this study underscores the impact of ankle restriction on sagittal plane kinematics as they relate to ACL injury.

## Conclusion

This study found a statistically significant difference between sagittal plane lower extremity joint kinematics in big mountain skiers under externally restricted ankle dorsiflexion conditions compared to unrestricted conditions. Differences in ankle dorsiflexion and knee flexion were statistically significant and consistent with increased risk of non-contact ACL injury mechanisms, such as BIAD and known ACL loading patterns. Ultimately, these findings indicate a need for further research on kinematics, kinetics, and ACL injury prevention in big mountain skiing.

## References

Almansoof, H. S., Nuhmani, S., & Muaidi, Q. (2023). Role of ankle dorsiflexion in sports performance and injury risk: A narrative review. *Electronic Journal of General Medicine*, *20*(5), em521. https://doi.org/10.29333/ejgm/13412

Baumbach, S. F., Brumann, M., Binder, J., Mutschler, W., Regauer, M., & Polzer, H. (2014). The influence of knee position on ankle dorsiflexion—A biometric study. BMC Musculoskeletal Disorders, 15(1), 246. https://doi.org/10.1186/1471-2474-15-246

Bere, T., Flørenes, T. W., Krosshaug, T., Koga, H., Nordsletten, L., Irving, C., Muller, E., Reid, R. C., Senner, V., & Bahr, R. (2011). Mechanisms of Anterior Cruciate Ligament Injury in World Cup Alpine Skiing: A Systematic Video Analysis of 20 Cases. *The American Journal of Sports Medicine*, *39*(7), 1421–1429. https://doi.org/10.1177/0363546511405147

Blackburn, J. T., & Norcross, M. F. (2014). The effects of isometric and isotonic training on hamstring stiffness and anterior cruciate ligament loading mechanisms. *Journal of Electromyography and Kinesiology*, *24*(1), 98–103. https://doi.org/10.1016/j.jelekin.2013.10.010

Böhm, H., & Senner, V. (2008). Effect of ski boot settings on tibio-femoral abduction and rotation during standing and simulated skiing. *Journal of Biomechanics*, *41*(3), 498–505. https://doi.org/10.1016/j.jbiomech.2007.10.019

Carroll, L. A., Kivlan, B. R., Martin, R. L., Phelps, A. L., & Carcia, C. R. (2021). The Single Leg Squat Test: A "Top-Down" or "Bottom-Up" Functional Performance Test? *International Journal of Sports Physical Therapy*, *16*(2), 360–370.

https://doi.org/10.26603/001c.21317

Cimino, F., Volk, B. S., & Setter, D. (2010). Anterior Cruciate Ligament Injury: Diagnosis, Management, and Prevention. *American Family Physician*, *82*(8), 917–922.

Della Croce, U., Cappozzo, A., & Kerrigan, D. C. (1999). Pelvis and lower limb anatomical landmark calibration precision and its propagation to bone geometry and joint angles. *Medical & Biological Engineering & Computing*, *37*(2), 155–161. https://doi.org/10.1007/BF02513282

Evans, J., Mabrouk, A., & Nielson, J. l. (2024). Anterior Cruciate Ligament Knee Injury. In *StatPearls*. StatPearls Publishing. http://www.ncbi.nlm.nih.gov/books/NBK499848/

Fong, C.M., Blackburn, J. T., Norcross, M. F., McGrath, M., & Padua, D. A. (2011). Ankle-Dorsiflexion Range of Motion and Landing Biomechanics. *Journal of Athletic Training*, *46*(1), 5–10. https://doi.org/10.4085/1062-6050-46.1.5

*FWT – Freeride World Tour – Home of Freeride*. (n.d.). Retrieved September 4, 2024, from https://www.freerideworldtour.com/

Hagins, M., Pappas, E., Kremenic, I., Orishimo, K. F., & Rundle, A. (2007). The effect of an inclined landing surface on biomechanical variables during a jumping task. *Clinical Biomechanics (Bristol, Avon)*, *22*(9), 1030–1036. https://doi.org/10.1016/j.clinbiomech.2007.07.012

Hébert-Losier, K., Supej, M., & Holmberg, H.-C. (2014). Biomechanical factors influencing the performance of elite alpine ski racers. Sports Medicine, 44(4), 519–533. https://doi.org/10.1007/s40279-013-0132-z

Holmberg, H.-C., Lindinger, S., Stöggl, T., Eitzlmair, E., & Müller, E. (2005). Biomechanical Analysis of Double Poling in Elite Cross-Country Skiers: *Medicine & Science in Sports*

*& Exercise*, *37*(5), 807–818. https://doi.org/10.1249/01.MSS.0000162615.47763.C8

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, *4*, 863. https://doi.org/10.3389/fpsyg.2013.00863

Lann Vel Lace, K., & Błażkiewicz, M. (2021). How does the ski boot affect human gait and joint loading? *Biomedical Human Kinetics*, *13*(1), 163–169. https://doi.org/10.2478/bhk-2021-0020

Mader, K., Pennig, D., Dargel, J., Gotter, M., Koebke, J., & Schmidt-Wiethoff, R. (2007). Biomechanics of the anterior cruciate ligament and implications for surgical reconstruction. *Strategies in Trauma and Limb Reconstruction*, *2*(1), 1–12. https://doi.org/10.1007/s11751-007-0016-6

Noé, F., García-Massó, X., Delaygue, P., Melon, A., & Paillard, T. (2020). The influence of wearing ski-boots with different rigidity characteristics on postural control. *Sports Biomechanics*, *19*(2), 157–167. https://doi.org/10.1080/14763141.2018.1452973

Petrone, N., Marcolin, G., Cognolato, M., Hofer, P., & Nachbauer, W. (2014). The Effect of Buckle Closure and Temperature on the In-vivo Flexibility of Ski-boots: A Pilot Study. *Procedia Engineering*, *72*, 630–635. https://doi.org/10.1016/j.proeng.2014.06.108

Petrone, N., Marcolin, G., & Panizzolo, F. A. (2013). The effect of boot stiffness on field and laboratory flexural behavior of alpine ski boots. *Sports Engineering*, *16*(4), 265–280. https://doi.org/10.1007/s12283-013-0133-z

Posch, M., Schranz, A., Lener, M., Tecklenburg, K., Burtscher, M., & Ruedl, G. (2021). In recreational alpine skiing, the ACL is predominantly injured in all knee injuries needing hospitalisation. *Knee Surgery, Sports Traumatology, Arthroscopy*, *29*(6), 1790–1796.

10.1007/s00167-020-06221-z

Shimokochi, Y., Ambegaonkar, J. P., Meyer, E. G., Lee, S. Y., & Shultz, S. J. (2013). Changing sagittal plane body position during single-leg landings influences the risk of non-contact anterior cruciate ligament injury. *Knee Surgery, Sports Traumatology, Arthroscopy*, *21*(4), 888–897. https://doi.org/10.1007/s00167-012-2011-9

Tchórzewski, D., Bujas, P., & Jankowicz-Szymańska, A. (2013). Body Posture Stability in Ski Boots Under Conditions of Unstable Supporting Surface. *Journal of Human Kinetics*, *38*, 33–44. https://doi.org/10.2478/hukin-2013-0043

Viola, R. W., Steadman, J. R., Mair, S. D., Briggs, K. K., & Sterett, W. I. (1999). Anterior Cruciate Ligament Injury Incidence Among Male and Female Professional Alpine Skiers. *The American Journal of Sports Medicine*, *27*(6), 792–795. https://doi.org/10.1177/03635465990270061701

Wilson, S. A., Dahl, K. D., Dunford, K. M., Foody, J. N., Zandiyeh, P., Turnbull, T. L., & Tashman, S. (2021). Ski boot canting adjustments affect kinematic, kinetic, and postural control measures associated with fall and injury risk. *Journal of Science and Medicine in Sport*, *24*(10), 1015–1020. https://doi.org/10.1016/j.jsams.2020.05.009

Yoneyama, Kagawa, Okamoto, & Sawada. (2000). Joint motion and reacting forces in the carving ski turn compared with the conventional ski turn. *Sports Engineering*, *3*(3), 161–176. https://doi.org/10.1046/j.1460-2687.2000.00060.x

Appendix A

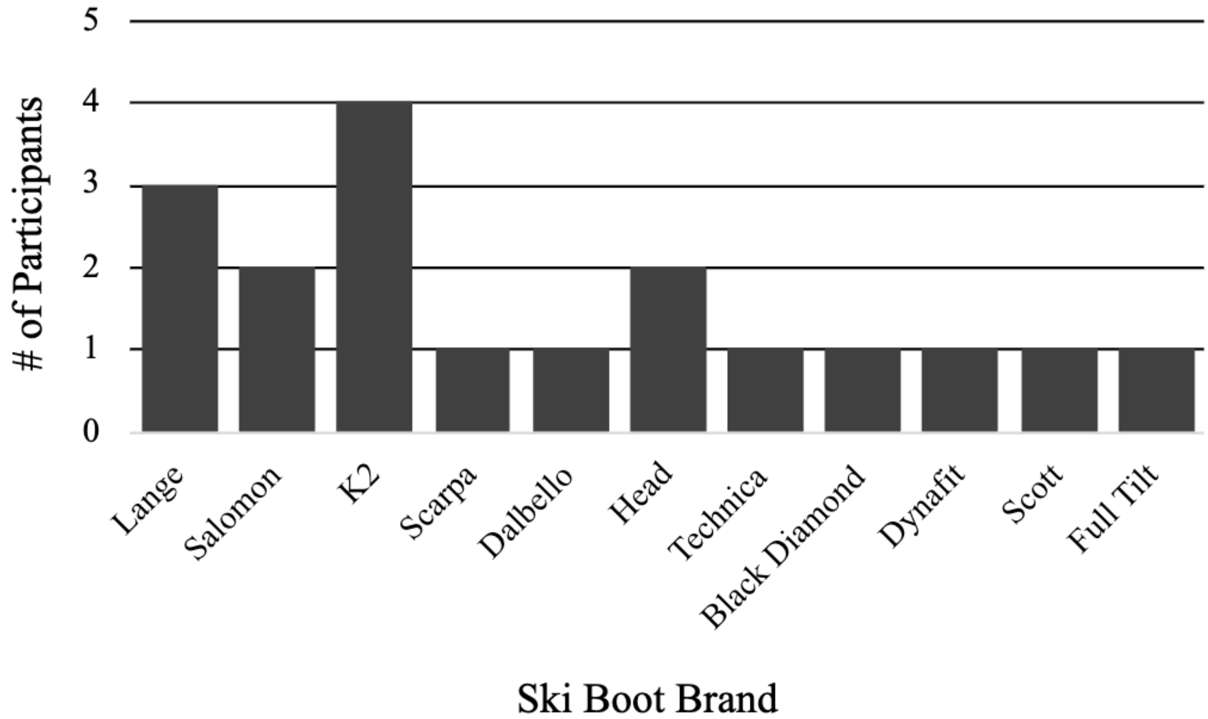


**Figure A1. Ski boot brands included in this study.** 11 ski boot brands were reported across 18 participants. K2 and Lange were the most predominant brands.