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# Biomechanical Adaptations to an Implemented Ramp Angle in Recreational Alpine Skiers

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# BIOMECHANICAL ADAPTATIONS TO AN IMPLEMENTED RAMP ANGLE IN RECREATIONAL ALPINE SKIERS

By

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Biomechanical Effects of an Implemented Ramp Angle in Recreational Alpine Skiers

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**ABSTRACT**

BIOMECHANICAL ADAPTATIONS TO AN IMPLEMENTED RAMP ANGLE IN RECREATIONAL ALPINE SKIERS

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Most ski boot-binding complexes have a negative ramp angle. This angle is not regulated or reported in the alpine ski industry, but may influence skier balance and pressure control. Thus, joint coordination and center of pressure maintenance in alpine skiers (n = 19) was investigated during simulated ski squat and balance tasks with increasing binding ramp angles (0°, 1°, 2°). Greater sagittal plane center of pressure excursions were observed with ski-booted tasks compared to barefoot conditions during squats and balance simulations. Squat tasks performed on skis resulted in more uncoordinated knee-ankle movement, however, this effect was reduced with the highest ramp angle. Further, increased hip driven movement coincided with decreased coordinated hip-knee movement. Barefoot balance tasks resulted in a reduced knee (knee-ankle coordination) and increased hip contribution (hip-knee coordination). Excursions during trials with higher ramps were more likely to be significantly greater than when barefooted. In conclusion, the addition of a boot-binding complex appears to increase sagittal plane excursions, increase uncoordinated movement (squat tasks), and reduce knee joint driven postural maintenance (balance tasks). Higher degrees of ramps may be associated with altered joint coordination that does not positively affect squat pressure maintenance, as well as reduced sagittal plane stability during balance challenges.

This thesis is dedicated to my loving parents, who have supported me through my years of education, encouraged me to grasp opportunities out of my comfort zone, and instilled in me a strong, dedicated work ethic. Further, my love for alpine skiing and the inspiration for this research emerged through the opportunities to learn and enjoy the sport that they provided throughout my childhood.

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## SYMBOLS/ABBREVIATIONS

3D ........ Three Dimensional
AL ........ Anterolateral
AM ........ Anteromedial
CA ........ Coupling Angle
CoM ........ Center of Mass
CoP ........ Center of Pressure
DP ........ Down Phase
GEn ........ Geometric Entropy
PO-P ........ Post-Perturbation
PR-P ........ Pre-Perturbation
RA ........ Ramp Angle
R0 ........ 0° Ramp Angle
R1 ........ 1° Ramp Angle
R2 ........ 2° Ramp Angle
UP ........ Up Phase

# CHAPTER I: JOURNAL MANUSCRIPT

## INTRODUCTION

Alpine ski-essential equipment such as boots and bindings often create declining ramp angles from heel to toe, however these angles are not reported or regulated in the recreational alpine ski industry. Many bindings create heel-to-toe ramps, ranging from a modest 0.66 mm difference to a large heel-toe discrepancy of 10 mm (Rossignol SAS-110) (Korich, 2016). A heel piece elevated 10 mm may equate to a negative ramp angle (RA) of greater than 2°, depending on the mounted length of the binding. DeRocco and Higgins (1999) patented bindings that create a negative RA and suggest the orientation will allow more "effective" ankle flexion, thus creating a body position that elicits "maximum vertical mobility range." Interestingly, slower giant slalom run times and greater forefoot pressure loading were observed with the instigation of a negative binding RA (Kröll, Birklbauer, Stricker, & Müller, 2006). However, it is currently unclear whether a negative RA would affect a skier's joint coordination and balance during ski tasks.

Though biomechanical effects of RAs have not been thoroughly investigated in ski tasks, similar tasks may provide insight to their balance and coordination consequences. When standing and ambulating, a compensatory posterior shift of the center of mass (CoM) occurred when a ramp angle was instigated via downhill slopes and high heeled shoes (Esenyel, Walsh, Walden, & Gitter, 2003; Ho, Blanchette, & Powers, 2012; Hong et al., 2014; Kuster, Wood, Sakurai, & Blatter, 1994; C.-M. Lee, Jeong, & Freivalds, 2001; D. Lee, Lee, & Park, 2015). Similarly, Fortin, Harrington, and Langenbeck (1997) suggest that a similar compensation may occur from the 3 cm heel height of figure skates. Weight lifting shoes with negative RAs decrease the sagittal plane displacement of the hip and forward lean of the torso during squat tasks (Legg, Glaister, Cleather, & Goodwin, 2017; Sato, Fortenbaugh, & Hydock, 2012). However, knee extensor activity and associated moments increase with weight lifting shoes, suggesting that increasing the RA of the shoe during squats may result in a greater movement contribution from the supporting knee musculature (Hartmann et al., 2016; Hartmann, Wirth, & Klusemann, 2013; D. Lee et al., 2015; Legg et al., 2017; Sato et al., 2012). The dynamic nature of a squat is comparable to movements during skiing, however, it is unclear whether similar postural and joint coordinative capabilities will result due to the limited range of motion available at the ankle joint when ski-booted.

Changes in sagittal plane joint mechanics with an imposed RA may be closely linked to the available range of ankle dorsiflexion. Supporting this, knee flexion range of motion was greater during squat and jump landing tasks when RAs were employed or ankle flexibility was greater (Dill, Begalle, Frank, Zinder, & Padua, 2014; Legg et al., 2017; Macrum, Bell, Boling, Lewek, & Padua, 2012). However, because a ski boot restricts ankle range of motion, a RA may not result in similar increases in knee range of motion during ski tasks.

The restrictive nature of the ski boot and terrain that requires a high level of sensory integration and cognition to navigate, makes ski balance a uniquely challenging task (Bennell & Goldie, 1994; Hébert-Losier, Supej, & Holmberg, 2014; Louis, Collet, Champely, & Guillot, 2012; Panjan, Supej, Rosker, & Sarabon, 2016; Powell & Williams, 2015). The addition of ski boots has been associated with both reduced sagittal plane stability, and when challenged in the mediolateral direction, greater vastus lateralis activation and knee flexion angles (Noé, García-Massó, Delaygue, Melon, & Paillard, 2018; Tchórzewski, Bujas, & Jankowicz-Szymańska, 2013). Thus, experienced skiers exhibit different joint mechanics than their counterparts with lesser experience (Müller et al. 1998). Knee joint extension is pivotal to create of an "up-unweighting" motion that is characteristic of the initiation of a parallel turn (Müller & Schwameder, 2003; Professional Ski Instructors of America, 2014). Müller and colleagues (1998) discovered that extension and "up-unweighting" occurred simultaneously in expert skiers, whereas less-experienced skiers did not execute extension at ideal time points.

Inexperience, ski boots, and RAs may thus affect the skier's control of the ski translation by changing the timing, magnitude, direction, and/or location of pressure application from the ski to the snow (Hébert-Losier et al., 2014; Panjan et al., 2016; Powell & Williams, 2015; Professional Ski Instructors of America, 2014). Supporting this, joint coordination changes after fatiguing lifting tasks were found in conjunction with increased anterior-posterior CoM excursion (Sparto, Parnianpour, Reinsel, & Simon, 1997). In ski boot balance tasks, Tchórzewski, Bujas, and Jankowicz-Szymańska (2013) suggested that the decreases in sagittal plane stability indexes, measured in beginner alpine skiers, were due to the inability to rearrange muscular coordination as Sparto and colleagues (2013) found. Importantly, during dynamic skiing, changes in CoM maintenance in relation to the base of support may have consequences to the location of the skier's center of pressure (CoP), further affecting the skier's ability to respond to perturbations throughout turns (Professional Ski Instructors of America, 2014).

The aims of the current study were to investigate the effects of a neutral, one degree, and two degree ski binding ramp angle on joint coordination and center of pressure during dynamic ski simulated squats and a novel ski balance task in recreational skiers. A within-subjects repeated measures design was employed, with experimental conditions (ramp angle) randomized and counter-balanced. It was hypothesized that a ramp angle would affect sagittal plane joint coordination and increase the center of pressure excursions and entropy which are negatively associated with balance maintenance during ski tasks.

## METHODS

### *Participants*

Participants (male = 11, female = 8, 27 ± 5 yrs, 1.76 ± 0.11 m, 73.9 ± 14.7 kg) were recruited from the general Marquette, MI, USA and Salzburg, Austria populations. Permission was obtained from the Institutional Review Board at Northern Michigan University (NMU; HS 17-868). Prior to testing, participants were screened with an informed consent (Appendix A), a Physical Activity Readiness Questionnaire (PAR-Q; Appendix B), and a Ski History Questionnaire (SH-Q; Appendix C). To minimize postural control differences participants were excluded from the study if they were not within 20-39 years of age with three or more seasons ski experience (Bennell & Goldie, 1994; Ekeland, Holtmoen, & Lystad, 1993; Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996; Shahudin et al., 2016). Questionnaires in the current study revealed that six participants had three to five seasons of experience (10+ days), and thirteen had partaken in eight or more seasons. Participants were intermediate or advanced "recreational skiers" defined by experience (intermediate = 8, advanced = 11; Type = 2.48 ± 0.5; see Appendix C); skill level was rated from the SH-Q and those categorizing as "expert" or "beginner" were excluded (Ekeland et al., 1993; Mildner, Lembert, & Raschner, 2010; Noe, 2005; Panjan et al., 2016). Lastly participants were excluded if lower limb deformation or injury, vestibular disorder, neurological disorder, lower limb reconstruction surgeries, and/or lower limb/foot fractures were present within one year. Volunteers were asked to refrain from pharmaceutical and recreational drugs that may affect balance for 24 hours, and to avoid strenuous exercise for three hours prior to the testing session.

*Measurements*

Four conditions were investigated during a simulated ski squat task and a novel ski balance task: barefoot (BF; consequently a 0° ramp angle), and ski-booted with a binding ramp angle of 0° (R0), 1° (R1), and 2° (R2). Participants used their personal ski boots for all booted tasks and ramp angles were accomplished via the see-saw mechanism of the SensoWip binding (Kröll et al., 2006). All participants used the same skis during the tasks, with ground contact area controlled to 1.2 m in length (see Appendix D).

During both types of task, Advance Medical Technologies Inc. (AMTI; Watertown, MA, USA) force platforms (Marquette: two AMTI FORCE OR6-7-2000, Salzburg: one AMTI FORCE BP6001200) recorded ground reaction forces at a sampling frequency of 250 Hz (Panjan et al., 2016). Additionally, three dimensional (3D) motion was captured (sampling frequency = 250 Hz; Sinclair, McCarthy, Bentley, Hurst, & Atkins, 2015) using a 10-camera Motion Analysis Corporation (MAC) system (California, USA) in Marquette, MI and a 16-camera Vicon Motion System (Oxford, UK) in Salzburg, Austria. Retro-reflective marker (USalz = 14 mm, NMU = 15 mm) placement for 3D motion capture was based on the cluster-based Cleveland Clinic lower body marker set with a global optimization approach (Lu & O'Connor, 1999). Markers were placed over ski boots or spandex clothing where appropriate; the medial/lateral malleolus markers were placed on the pivot point between the upper and lower boot, toe markers were placed at a distal third of the distance from the tip of the boot to ankle markers, and the heel marker was placed on the posterior side of the boot at the same height as the toe.

*Squat Tasks*

The squat task was defined as ten dynamic squats executed to a metronome-controlled rhythm (36 bpm) that simulated the tempo of skiing (Seifert, Kröll, & Müller, 2009). All participants were instructed to squat to a depth approximating a 90° knee flexion angle. Skis were secured to the test surface with the outer edges creating a stance width equal to the distance between greater trochanter markers.

*Balance Tasks*

The effects of 45° anterolateral (AL) and anteromedial (AM) directional balance perturbations were investigated with the skier standing one-legged in each of the four experimental conditions. Three trials in each direction were performed successively for each ramp angle, totaling 6 balance tasks completed per experimental condition. Participants performed the balance tasks on their dominant leg, which was determined by the participant's preferred leg used to kick a ball (Vuillerme, Sporbert, & Pinsault, 2009). The balance perturbation mechanism was created by suspending a medicine ball (USalz = 4 kg, NMU = 4.54 kg) at mid-torso height for each participant. The ball was released from a set height off the floor in order to swing in a pendulum-fashion toward the participant.

A perturbation trial began when the participant was cued to stand unmoving on their dominant leg. The participant would then begin reading numbers (1-5) from a randomized slideshow placed directly anterior to them. Upon the word "go," the medicine ball was released and participants would turn their torso to catch the ball. Once caught, the participant would return to reading numbers in an anterior-facing orientation until cued to stop by the researchers. Each trial lasted approximately 16 s from the start of one-legged balance to the stop cue.

*Test Set-up and Warm-up*

After a six minute treadmill run at a self-selected pace, participants were familiarized with the squat and balance tasks. During this time, squat depth was establish and learned, followed by practice of the metronome controlled tempo. Squat tasks were performed until the participants felt comfortable with the task. Balance tasks were learned through a progression of nine familiarization trials per perturbation direction. Trials 1-3 were accomplished bipedally, with the participant's torso facing the perturbation mechanism. Trials 4-6 simulated the measured balance task, however they were also completed bipedally. The final three trials were performed exactly as they would be measured during the test.

*Test Plan*

BF conditions were performed first, followed by R0, R1, and R2 in a randomized and counterbalanced order between participants (Figure 1). The first participant was tested in the AL perturbation direction first (followed by AM), with an alternating AM-AL pattern ensuing for the rest of the participants.

*Data Analysis*

Analysis of the squat tasks was limited to the final three squats performed in each condition, with resulting data averaged across the three measures. Additionally, squat down phase (DP) and up phase (UP) were analyzed as two independent events. The start of the DP and UP were determined by the "transition points": where the pelvis segment assumed a resultant velocity of zero. Analysis of the balance tasks was limited to the third trial and two defined phases: pre-perturbation (PR-P) and post-perturbation (PO-P). PR-P and PO-P were defined as the five seconds before and after (Goldie, Evans, & Bach, 1992) the peak negative acceleration of the ball, which was calculated via the resultant vector of the ball's x-y-z coordinates and occurred at the ball's initial release.

Marker kinematics were digitized and filtered using a 9 Hz low-pass Butterworth filter (Hewett et al., 2005). Visual 3D x64 Professional (v6.01.18; Germantown, MD USA) was used to calculate sagittal plane joint angles of the ankle, knee and hip during each of the tasks via the six degree of freedom model defined by Selbie, Hamill, and Kepple (2013). Joint coordination was assessed using angle-angle diagrams and modified vector coding using methodology from Needham, Naemi, and Chockalingam (2014). Coupling angle (CA) was assessed as a percentage of the squat that was spent in each coordinative pattern: when the movement was driven primarily by the proximal joint, distal joint, or with the two joints in-phase, or anti-phase (Figure 2). Hip-knee and knee-ankle coupling were assessed separately across the squat DP and UP, as well as the balance task PR-P and PO-P.

Kinetic data were filtered using a 40 Hz Butterworth bidirectional cutoff (Fransz, Huurnink, de Boode, Kingma, & van Dieën, 2015). Center of pressure (CoP) was assessed via the global coordinates of Mx and My moments. At NMU, this required the merging of two force plate outputs via the calculations supported by Exell, Gittoes, Irwin, and Kerwin (2012). From the global coordinates, the CoP length of excursion and 95% confidence circle area were calculated for each of the phases in the squat and balance tasks (Prieto et al., 1996). Geometric entropy (GeoEn) was also calculated from the global CoP coordinates during each phase, using the equation (Sibella, Frosio, Schena, & Borghese, 2007):

$$GeoEn = \ln \frac{2 * CoP\ Path\ Length}{Convex\ Hull} \tag{1}$$

Where GeoEn = Geometric entropy

CoP = center of pressure

Convex hull = the smallest envelope encompassing all data points

*Statistical Analysis*

All statistics were analyzed using SPSS Statistics (v.24). Group average CAs throughout the squat were created for each joint pair (DP + knee-ankle; UP + knee-ankle; DP + hip-knee; UP + hip-knee) and ramp conditions were compared with a nonparametric Friedman test as significant skewness and kurtosis were detected. Significance across median differences was then assessed by a Wilcoxon Signed Ranks test and evaluated to an adjusted alpha for six comparisons ($\alpha = 0.0083$). Two-way repeated measures ANOVAs ($\alpha = 0.05$) were used to compare CA coordination frequency (percent in each movement pattern) across ramp conditions and leg dominance during the squat. The squat DP, UP, and joint pairs (hip-knee; knee-ankle) were assessed separately. All CoP measures (entropy, area, excursions) were assessed across ramp condition and squat phase with two-way repeated measures ANOVAs. Partial eta squared ($\eta_p^2$) was calculated using SPSS to provide estimates of effect size for the repeated measures (Heiderscheit, Hamill, & van Emmerik, 2002). Interpretations of small ($\eta_p^2 = 0.01$), medium ($\eta_p^2 = 0.06$), and large ($\eta_p^2 = 0.14$) effects were based on recommendations by Cohen (1988).

Balance task average CA, CA coordination frequency, and CoP Entropy were assessed parametrically with three-way mixed measures ANOVAs for both joint pairs ($\alpha = 0.05$) and subsequent $\eta_p^2$ calculation. Ramp condition and time (PR-P; PO-P) were assessed as within-subject measures, while perturbation direction (AL; AM) was assessed between subjects. A non-parametric Friedman test was used to identify significant differences in CoP area and excursion (total; sagittal; frontal) for ramp conditions and PR-P/PO-P. Perturbations in the AL and AM directions were assessed separately. Significance ($\alpha = 0.05$) was further evaluated with a Wilcoxon Signed Ranks test across ramps PR-P and PO-P (six comparisons each), and PR-P versus PO-P (four comparisons).

## RESULTS

### *Squat Tasks*

Mean CA was significantly different between all conditions for the UP of both the knee-ankle and hip-knee coupling ($p < 0.0083$; Figure 3). Additionally, knee-ankle CAs during the squat DP were significantly larger in all ski conditions compared to BF, as well as R2:R0 and R2:R1 (Table 1). Finally, BF average CA for the DP hip-knee pairing was larger than all ski conditions ($p < 0.0083$) and not significantly different between R0-R2 (Table 1).

When knee-ankle CA phase frequency was assessed, knee driven coordination made the greatest contribution to both the DP (82.5 – 83.8%) and UP (86.0 – 88.5%) of the squat task in all experimental conditions (Table 2). In-phase knee-ankle coordination was greater in ski tasks compared to BF through the entire squat, except R2 in the squat UP (Table 2). The percentage of squat spent in-phase was significantly lower in the R2 condition as compared to R0 during the squat DP (mean difference = -2.4 ± 0.8, p = 0.039; Table 1). No additional effects were observed between ramp interventions R0-R2 during other coordination phases. Additionally, frequency was not significantly different between the dominant and non-dominant legs.

The greatest percentage of squat was spent in anti-phase hip-knee coordination during both DP and UP (88.2 - 94.6%; Table 3). This indicates these two joints were coordinated in flexion (DP) or extension (UP), as shown in Figure 2. Additionally, a greater percentage of time was spent with primarily hip-driven angular movement during the UP when ramp conditions were compared to BF (Table 3). This relationship was reflected only between BF and R0 for the squat DP. In-phase hip-knee coordination increased from BF to R0 and R1 (1.3 ± 0.3%, 1.0 ± 0.2%, respectively) during the squat DP, however this relationship was not seen with R2.

The BF condition significantly differed from all ski-booted tasks in CoP area, total excursion, and sagittal plane excursion (Table 4; Appendix E: Figures 10, 11). Of these measures, a significant ramp/phase interaction was only seen with CoP area ($p = 0.001$, $\eta_p^2 = 0.355$; Appendix E: Figure 10). No differences in frontal plane excursion were observed across any of the experimental ramp conditions ($p = 0.063$, $\eta_p^2 = 0.144$), however there was a significant difference between DP and UP ($p < 0.001$, $\eta_p^2 = 0.753$, DP – UP = 1.0 mm; Appendix E: Figure 12). Finally, GeoEn was significantly greater during the BF condition as compared to R1 ($p = 0.043$, $\eta_p^2 = 0.272$; Table 4), this difference contributed to a significant interaction of ramp and squat phase ($p = 0.002$, $\eta_p^2 = 0.419$; Appendix E: Figure 13).

*Balance Tasks*

Hip-knee CAs were not significantly affected by perturbation time (PR-P vs. PO-P), however perturbation direction was significantly different ($p = 0.002$, $\eta_p^2 = 0.004$; AL – AM = 1.50°; Figure 4). Mean knee-ankle coupling was different pre-to-post perturbation ($p < 0.001$; Figure 5). For both joint couples, ski ramp conditions resulted in altered average CA compared to barefoot ($p < 0.001$; Table 5). The only difference between ski conditions was observed between R1 and R2 for the knee ankle couple ($p = 0.017$; Table 5). The percent of balance task spent in proximal joint dominant movement is the only joint coupling frequency measure that reports similar differences between BF and ski-booted conditions for both the hip-knee and knee-ankle joints ($p < 0.05$; Table 5; Appendix F: Table 7, 8).

Greater CoP area and excursion (total, sagittal, and frontal plane) was found PO-P as compared to PR-P using Wilcoxon Signed Ranks evaluations for both directional perturbations ($p < 0.001$; Figure 6). Ramp conditions did not significantly differ in any of the PR-P phases, with the exception of frontal plane CoP excursion during the AM trial (R2 was significantly less than BF and R1; $p = 0.013$ and $0.022$, respectively). All ski-booted conditions resulted in significantly higher PO-P CoP sagittal plane excursions and area during the AM trials ($p < 0.05$; Figure 6). During the AL trials, the only differences found were between BF and R2 PO-P ($p < 0.05$; Figure 6). Finally, PO-P CoP excursion in the frontal plane was reduced in ski-booted conditions as compared to barefoot during the AL and AM trials, with the exception of the AM

BF to R2 comparison Po-P (Figure 6). Two ramp comparisons were also different: R1 resulted in less excursion than R2 (AL trial) and R0 was similarly smaller when compared to R2 (AM trial).

Geometric Entropy assessed PR-P and PO-P indicated there was a significant reduction in the entropic chaos after the perturbation for both AL and AM trials ($p < 0.001$, $\eta_p^2 = 0.680$). Though ramp conditions were not statistically different, a significant interaction was observed between ramp and time (Figure 7).

**DISCUSSION**

Ski boot and binding complexes are an essential component of the sport of recreational alpine skiing. The balance and postural effects of restricting the ankle via a ski boot has been the topic of many investigations because it poses significant challenges for alpine skiers (Noé, Amarantini, & Paillard, 2009; Noé et al., 2018; Tchórzewski et al., 2013). However, ski bindings have many makes, models, and characteristics similar to the variety that exists in ski boots (flex, inclination angle, buckle mechanisms, etc.). This study investigated the effects of one principal, yet overlooked, characteristic of alpine ski bindings: the ramp angle created from the elevation of the heel piece compared to the toe piece. To accomplish this purpose, CoP and sagittal plane joint coordination were investigated during a dynamic ski-simulated squat and a novel ski-balance task.

*Squat Tasks*

The addition of the ski boot-binding complex altered the joint coordination and CoP measures during the squat tasks compared to when the participants performed the same tasks unshod. During the UP and DP of the squat, participants spent the greatest amount of time (88.2 – 94.6%) in antiphase hip-knee coordination. Because of the joint model used, this indicates that these two joints were spending more time performing coordinated coupled movements (i.e. simultaneously extending). Interestingly, during the UP of the squat the antiphase contribution was smaller with the addition of the ski boot-binding complex, where participants instead spent a greater amount of time in proximal (hip) driven movement (Table 3, Figure 3). These findings explain the decreased average CA measured during the UP for the BF task (Table 1). Differences found in the average CA and frequencies during the DP suggest an increased contribution in-phase coupling (indicating uncoordinated movements) during R0 and R1 as compared to BF (Table 3). Increases in uncoordinated movement were also seen with knee-ankle coupling, supported in measurements of R0 and R1 compared to BF.

Movement coordination differences appear to occur at the beginning and end of the range of motion of the squat (Figure 3). These time points of maximal flexion and extension are pivotal points in the execution of a ski turn (Müller & Schwameder, 2003). Increased uncoordinated movement at the transition points may reduce the simultaneity of the extension and "up-unweighting" that Müller and colleagues (1998) reported in expert skiers. Interestingly, this effect had a tendency toward a lesser in-phase contribution with increasing ramp angle (Table 2 & 3), suggesting that a greater ramp angle may in fact help skiers execute squats closer to their native coordination patterns (barefoot conditions) while restricted in ski boots. Lesser in-phase contribution with R2 in the squat DP for both coordination couples indicates that the increased percentage of time spent in the uncoordinated angular movement likely doesn't explain the increased run time measured with a positive RA by Kröll et al. (2006). However, the coordinative pattern of movement may have further consequences on the translation and pressure distribution of the ski on the snow. This ability is greatly tied into the magnitude and location of the CoP. For example, "up-unweighting" from joint extension can affect the magnitude of pressure from the ski to the snow and ultimately the skier's speed and edge control: too much pressure may result in an inability to rotate the skis, whereas too little may result in loss of edge control (Professional Ski Instructors of America, 2014).

Coordination changes can not only affect the magnitude of pressure, but also the location of pressure and balance maintenance. For example, coordinative differences such as earlier extension and decreased knee/hip ranges of motion were associated with decreased postural stability during dynamic fatiguing lifting tasks (Sparto et al., 1997). Measured center of pressure area and excursion (sagittal and total) were all significantly greater in the ski conditions as compared to the BF (Table 4). Counterintuitively, greater excursion area and distance in the ramp conditions did not coincide with greater GeoEn constants for the respective comparisons (Table 4). In fact, the higher entropy recorded indicates that there was higher chaos of the system during BF conditions compared to R1 ($p = 0.043$; with a tendency toward significance in R0 and R2: $p = 0.076$ and $0.077$, respectively). Mancini and Horak (2010) supported that a smaller base of support area makes dynamic posturography a more difficult task. Because the addition of skis makes the base of support multiple times larger than the BF conditions, this may contribute to the slightly more favorable GeoEn measures during ski tasks.

The calculation of GeoEn is directly related to path length per convex hull (Equation 1), so a potential explanation for lesser CoP chaos may be in the restriction of CoP sagittal plane excursion during BF conditions. In fact, the total excursion appeared to be compromised primarily from the sagittal plane deviations for the ski booted tasks (example R0 DP: sagittal excursion = $24.4 \pm 1.3$ mm, frontal excursion = $2.0 \pm 0.1$ mm, and total excursion = $24.9 \pm 1.2$ mm), this comparably minimal frontal plane excursion would significantly reduce the area of the convex hull as compared to one that sees similar deviation in the x and y planes (example BF:

sagittal excursion = 3.5 ± 2.0 mm, frontal excursion = 2.5 ± 1.4 mm, total excursion = 5.1 ± 2.1 mm). Although there is less excursion happening in the BF CoP measures, the area of the convex hull in relation to the path length is greater with BF conditions, resulting in more chaos of the system (Sibella et al., 2007). The nature of the ski boot to allow some sagittal plane flex, coupled with a greater base of support area in the sagittal plane, likely contributed to this difference in sagittal excursion contribution. Supporting this theory, a significant ramp by phase interaction is evidenced in the analysis of GeoEn ($p = 0.024$, $\eta_p^2 = 0.206$), which is primarily occurring from the BF condition (Appendix E: Figure 13). Importantly, reduced frontal plane excursion was measured during the UP of the squat as compared to the DP across all conditions ($p < 0.001$; Appendix E: Figure 12). This suggests that the ramp vs. phase interaction seen in the GeoEn results may have occurred because of the reduction in frontal plane motion during the squat UP. Thus, GeoEn comparisons of BF to ramp conditions during squats may not be appropriate to compare the magnitude of entropic chaos as an indicator of balance maintenance because of the greater base of support area. Ultimately, greater CoP excursions measured in ski tasks may be associated with reductions in postural stability as a product of joint contribution changes similar to the findings of Sparto and colleagues (1997).

Comparisons between GeoEn and CoP between the three ski-booted tasks did not yield any statistical differences to support those found in average CA results. During the squat UP of both coordination couples, all RAs were significantly different from one another, however non-statistically different frequency distributions can explain this effect. The differences in CA during the knee-ankle DP can be explained by the previously discussed significant reduction in in-phase joint coordination. However, because there were no corresponding differences in force measurements, it is unclear whether these coordinative changes affect the dynamic balance maintenance of a skier. The force measures reported provide information about the movement of the CoP, however for ski-movement specificity, the location of the CoP within the base of support may provide further insight to whether these coordination changes may affect the skier's ability to accomplish rotary and favorable magnitude/location of pressure (Professional Ski Instructors of America, 2014).

Ultimately, further investigation into the joint coordination changes seen across the squat tasks between ramps and ski-booted compared to unshod may provide more insight to how it may affect the performance of a skier. For example, statically, excessive ankle flexion coupled with knee extension tends to anteriorly shift the CoM, which would subsequently shift the CoP anterior (Professional Ski Instructors of America, 2014). Joint coordination changes suggest that postural changes are likely occurring during ski movement, however measures of central tendency may not be able to pinpoint phase-specific differences in CoP and angular movement. Thus, tracking both CAs and force by statistical parametric mapping may provide additional insight into the effects of RAs on skier coordination and balance control.

*Balance Tasks*

The CoP area, excursion, and entropy measures all support that significant differences exist pre-to-post perturbations ($p < 0.01$). Area, sagittal, and frontal plane excursions increased after perturbations, indicating that the perturbation mechanism did affect the participants. Interestingly, for the CA and CA phase frequencies PR-P and PO-P phases had no effect on the hip-knee CA, and arguably in the knee-ankle CA ($p < 0.001$, $\eta_p^2 = 0.008$). Interestingly, when viewing mean CA plots, the perturbation is clearly visible with large comparative deviations after the perturbation was imposed. Similar to the squat tasks, a measure of central tendency may in fact wash out this effect because of the overreaching “rebound” to baseline seen in Figures 4 and 5.

The results of the CoP measurements suggested that differences are primarily seen in the BF to ski booted conditions (AM area, AM sagittal excursion, AL and AM frontal plane excursion; Table 6, Figure 6). Lesser area and sagittal plane excursion was found with the BF trial during AM perturbations, whereas it exhibited greater frontal plane excursion (except AM R2) compared to RAs. These results support the findings of Tchórzewski et al. (2013), who found that sagittal plane stability was reduced when beginner skiers (unaccustomed to the mechanistic support of the ski boot) as compared to barefoot conditions. Further supporting these findings, Bennell and Goldie (1994) contend that balance task performance and postural control in fact are reduced with high levels of ankle support, which occurs in a booted condition. Because sagittal plane excursion and CoP area were unaffected by varying degrees of binding ramps, and no tendency was observed across the conditions, it is likely that the restrictive nature of the boot is the source of the CoP differences. Interestingly, R2 significantly differed from the BF condition in AL area, sagittal excursion, and AM total excursion, when no other comparison was significant (Table 6). This may indicate that with increasing ramp angles, the chances of excursion differing significantly from BF conditions may increase, however this dose effect theory is not supported by statistical differences between the ramps. Further, there is potential that effects are seen with an asymptotic response beyond a certain level, however additional RAs would need to be investigated to confirm this type of response.

Mean CA for ramp conditions suggested significance across the ramp conditions, however this effect size was minimal in both: hip-knee $\eta_p^2 = 0.01$; knee-ankle $\eta_p^2 = 0.005$. The post hoc tests suggested that each of the ski ramps were significantly different from the BF conditions, with BF resulting in a larger CA in both joint pairs. Although these were minimal effects, analysis of the time spent in each coordinative pattern supported that both joint pairs had significant differences in the proximal joint movement. For hip-knee coordination with ramp conditions, participants spent 2-3% less time in hip driven movement. Knee-ankle coordination coupling supported that ramp conditions decreased the amount of time spent in knee driven movement by approximately 6%. Noé et al. (2018) found that active postural control increased with a mediolateral challenge, suggesting that the joint coordination changes found in the current study may be reflecting similar postural control mechanisms with AL and AM perturbations. Ultimately, although mean CA measures of central tendency cannot soundly support the difference between ski conditions and BF, the frequency measures support that joint coordination, primarily regarding the knee, are affected by the addition of a boot binding complex. These joint changes may affect the maintenance/movement of the CoP in relation to the base of support, thus contributing to CoP differences reported in this study.

Similar to the frontal plane excursion seen during the squat tasks, barefoot conditions had greater frontal plane excursions than all RA conditions during AL perturbations, and greater than R0 and R1 during AM perturbations. Interestingly, R2 also exhibited greater frontal plane excursion than R0 (AM) and R1 (AL). Due to the non-parametrically run tests, AM and AL perturbation directions were not statistically compared except for those measures that were run parametrically with 3 way ANOVAs. Of these, mean knee-ankle CA and entropy both indicated no significant differences were found between the directions; and though with a negligible effect size, hip-knee CA reported a significant difference. Thus, the directions of perturbations likely did not have an effect on recreational skiers in the current study.

Entropy measures were not significantly different across experimental conditions during either directional perturbation or time of perturbation. Theoretically, because several of the ramp conditions had greater CoP area, sagittal excursion, and total excursion compared to BF (Figure 6), the chaos of the system should predictably increase compared to BF conditions. However, similar to the discussion of squat entropy, the BF conditions exhibited greater frontal plane excursions thereby increasing the convex hull and the subsequent chaos of the system compared to the ramp conditions. Although it is through different mechanisms (increases in sagittal vs frontal plane excursion), this is likely the reason no significant differences exist amongst our GeoEn findings between BF and ski-booted conditions. Surprisingly, a significant phase effect PR-P to PO-P indicated reductions in GeoEn after the ball was caught. The researchers postulate that this may occur due to two potential reasons: 1) the movement of the upper limbs was not controlled PR-P, however the upper limb were constrained during the PO-P due to the task of holding the ball, 2) with the challenge of returning to quiet standing, increased focus and postural control may have been employed by participants, thus reducing entropic chaos of the system. This second theory is supported in the findings of Noé et al. (2018), who found that participants restricted in ski boots increased active postural strategies in response to a mediolateral perturbation challenge. However, most importantly for the purpose of the current study, entropy measures were not affected by the degree of ramp angle elicited by the bindings.

Both the squat and balance tasks produced evidence that R2 may differ in both coordination and CoP measures. As discussed, the R2 CAs had a tendency to return closer to the percentage of phase observed in BF CA frequencies. The balance task trials suggest the opposite effect with a greater CoP sagittal excursion and area observed in several trials. Supported by anecdotal reports from participants, the researchers postulate that the ramp angle is large enough in the R2 condition to become noticeable to the participants. Thus, specific conscious postural adaptations may occur as a result, causing the highest ramp angle to differ from the neutral and one degree conditions. This theory has been postulated by researchers investigating similar ramp conditions such as figure skates and the use of high heeled shoes (Fortin et al., 1997; C.-M. Lee et al., 2001). If this is in fact the case, then future studies may consider investigating ramp angles higher than two degrees and evaluating more trials in an effort to reduce test-retest variability.

*Limitations*

Attempts were made to reduce the variability of the data through strict participant criteria and directed task-learning, however a high degree of variability in the data still existed. Because of this variability, effects of the four experimental conditions during the balance tasks were evaluated with non-parametric statistics to compare central tendency of the CoP area and excursion results as they were all greatly skewed and kurtotic. Attempts to transform the data did not correct the kurtotic nature of the data. Because so many comparisons were assessed, and the alpha level was not corrected across comparisons, chances of Type 1 errors in the non-parametric CoP data are greater. However, these data were assessed with parametric tests after log transformations to *near* normal distributions (subsequent kurtosis = 3.38, 2.98, 3.31) and found similar differences between the BF and ramp conditions.

Further, the significant CoP excursions and area could potentially be explained by elevation of the participant's foot off the ground elicited by the SensoWhip binding mechanism. Although the distance from the floor was less in BF conditions, the ski tasks had similar advantages over the BF: including a greater base of support area and higher proprioceptive feedback from the boot (Bennell & Goldie, 1994; Mancini & Horak, 2010). Thus, the researchers believe the investigation was adequate to produce conclusions about the boot-binding complex.

## CONCLUSIONS

Evidence in the current study suggests that the addition of an alpine boot-binding complex alters the joint coupling of the lower limbs and CoP sagittal plane excursion during ski-simulated squats. During the ski tasks, greater excursions coupled with uncoordinated movements associated with the beginning and end of the dynamic squat range of motion are likely to affect the skier's ability to control and translate the ski. Small reductions in uncoordinated movement observed with R2, coupled with similar sagittal plane excursion and area (compared to R0 & R1), suggests that higher degrees of RAs may alter joint coordination patterns without subsequent effects on CoP excursion and area. Thus, total movement of the CoP during dynamic ski tasks is likely not significantly altered with increasing RAs, however further investigation into the location of the CoP in relation to the base of support may provide further information into performance implications of the CoP movement.

Similarly, balance task performance in the current study suggests that when the participant was unshod, lesser CoP sagittal plane excursion and area is observed along with greater frontal plane excursion when compared to ski-booted tasks. These CoP differences coincided with shifts in CA frequency that were associated with greater knee-driven movement during ski-booted tasks. Due to a greater frequency of significant CoP differences between R2 and BF conditions across the AL and AM trials, this may indicate R2 has a greater tendency to exceed BF measurements.

To the authors' knowledge, the current study is the first to document significant postural changes and CoP excursions while dynamic and balance tasks were performed on the full ski set-up.  Although the highest ramp angle was associated with a tendency toward similar postural coordination as unshod conditions, center of pressure area and excursions in the sagittal plane do not suggest this is beneficial in the reduction of CoP movement in either balance or dynamic tasks.  Thus, further investigation into the specific phase pattern interactions may provide further insight into the affects the degrees of ramp angle have on skier performance and fall risk.

## TABLES

Table 1 – Mean differences in squat couple angle (degrees).

| Comparison | DP Knee-ankle | UP Knee-ankle | DP Hip-knee | UP Hip-knee |
|---|---|---|---|---|
| BF – R0 | -16.57* | 61.92* | -15.80* | -17.59* |
| BF – R1 | -9.48* | 46.59* | -15.79* | -17.02* |
| BF – R2 | -21.62* | 43.56* | -15.72* | -16.68* |
| R0 – R1 | 7.09 | -15.33* | 0.01 | 0.56* |
| R0 – R2 | -5.05* | -18.36* | 0.09 | 0.90* |
| R1 – R2 | -12.14* | -3.03* | 0.08 | 0.34* |

* = Significant at $p < 0.0083$

Table 2 – Knee-ankle coupling frequency, percent of squat phase (± SD).

| | **Down Phase** | | | | **Up Phase** | | | |
|---|---|---|---|---|---|---|---|---|
| | **BF** | **R0** | **R1** | **R2** | **BF** | **R0** | **R1** | **R2** |
| Knee | 82.5 ± 3.7 | 83.6 ± 0.6 | 82.5 ± 2.3 | 83.8 ± 2.8 | 86.0 ± 3.3 | 88.5 ± 1.1 | 86.4 ± 1.9 | 87.5 ± 1.8 |
| Ankle | 0.5 ± 0.1 | 2.3 ± 0.3* | 1.8 ± 0.2* | 2.2 ± 0.3* | 1.1 ± 0.1 | 1.7 ± 0.2 | 1.6 ± 0.2 | 1.6 ± 0.2 |
| In | 0.9 ± 0.2 | 6.4 ± 0.9* | 5.2 ± 0.7* | 4.0 ± 0.6*x | 0.6 ± 0.3 | 3.8 ± 0.8* | 6.1 ± 1.8* | 4.8 ± 1.9 |
| Anti | 15.0 ± 3.7 | 6.7 ± 1.5 | 9.3 ± 2.2 | 8.9 ± 2.4 | 8.5 ± 3.2 | 2.0 ± 0.5 | 1.9 ± 0.4 | 1.8 ± 0.4 |

BF = barefoot; R0, R1, R2 = ski binding ramp angles of 0°, 1°, and 2°, respectively. Coupling pattern = knee, ankle, in-phase, and anti-phase.
* = Significantly different from BF condition ($p < 0.05$)
x = significantly different from R1 condition

Table 3 – Hip-knee coupling frequency, percent of squat phase (± SD).

| | Down Phase | | | | Up Phase | | | |
|---|---|---|---|---|---|---|---|---|
| | **BF** | **R0** | **R1** | **R2** | **BF** | **R0** | **R1** | **R2** |
| Hip | 1.1 ± 0.2 | 3.7 ± 0.6* | 2.8 ± 0.5 | 2.0 ± 0.4 | 0.7 ± 0.2 | 6.6 ± 1.1* | 7.0 ± 1.1* | 4.7 ± 0.9* |
| Knee | 5.6 ± 1.6 | 3.1 ± 0.8 | 2.5 ± 0.7 | 3.5 ± 0.8 | 3.5 ± 0.8 | 4.1 ± 1.0 | 3.2 ± 0.7 | 5.5 ± 1.0 |
| In | 0.3 ± 0.1 | 1.6 ± 0.3* | 1.3 ± 0.2* | 0.8 ± 0.2 | 0.3 ± 0.2 | 0.1 ± 0.1 | 0.3 ± 0.1 | 0.3 ± 0.1 |
| Anti | 89.6 ± 1.5 | 88.5 ± 0.8 | 90.0 ± 0.8 | 90.2 ± 0.8 | 94.6 ± 0.8 | 88.2 ± 1.5* | 88.5 ± 1.1* | 88.5 ± 1.0* |

BF = barefoot; R0, R1, R2 = ski binding ramp angles of 0°, 1°, and 2°, respectively. Coupling pattern = hip, knee, in-phase, and anti-phase.

* = Significantly different from BF condition ($p < 0.05$)

Table 4 – Differences in center of pressure mean comparisons (squat).

| Comparison | Entropy | Area (mm) | Total Excursion (mm) | X Excursion (mm) | Y Excursion (mm) |
|---|---|---|---|---|---|
| BF – R0 | 0.20 | -53.87* | -23.44* | -24.24* | 0.29 |
| BF – R1 | 0.24* | -65.01* | -22.68* | -23.46* | 0.38 |
| BF – R2 | 0.20 | -64.56* | -23.21* | -24.09* | 0.45 |
| R0 – R1 | 0.04 | -11.13 | 0.76 | 0.78 | 0.09 |
| R0 – R2 | 0.003 | -10.69 | 0.23 | 0.15 | 0.16 |
| R1 – R2 | -0.04 | 0.44 | 0.53 | -0.63 | 0.07 |

BF = barefoot; R0, R1, R2 = ski binding ramp angles of 0°, 1°, and 2°, respectively.
* = Significant at $p < 0.05$

Table 5 – Differences in CA and proximal joint CA frequency (balance).

| **Comparison** | **Hip – knee couple** Average CA (degrees) | Frequency (hip) (percent) | **Knee – ankle couple** Average CA (degrees) | Frequency (knee) (percent) |
|---|---|---|---|---|
| BF – R0 | 1.46* | -2.37* | 1.85* | 5.86* |
| BF – R1 | 2.36* | -3.00* | 3.18* | 6.03* |
| BF – R2 | 2.08* | -2.00* | 1.50* | 6.49* |
| R0 – R1 | 0.90 | -0.63 | 1.33 | 0.17 |
| R0 – R2 | 0.62 | -0.22 | -0.34 | 0.63 |
| R1 – R2 | -0.28 | -0.40 | -1.67* | 0.46 |

BF = barefoot; R0, R1, R2 = ski binding ramp angles of 0°, 1°, and 2°, respectively.
* = Significant at $p < 0.05$

Table 6 – Differences in CoP medians during balance tasks.

| Comparison | Area (mm) | | Excursion | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Total (mm) | | X (mm) | | Y (mm) | |
| | AL | AM | AL | AM | AL | AM | AL | AM |
| BF – R0 | -6.16 | -9.95* | 0.67 | -2.56 | 0.61 | -3.14* | 2.05* | 2.14* |
| BF – R1 | -4.83 | -8.75* | 0.59 | -0.64 | -0.50 | -1.11* | 2.50* | 1.74* |
| BF – R2 | -9.01* | -5.96* | -2.28 | -2.15* | -2.28* | -2.89* | 1.46* | 1.41 |
| R0 – R1 | 1.33 | 1.21 | 0.08 | 1.92 | -1.11 | 2.03 | 0.45 | -0.40 |
| R0 – R2 | -2.86 | 3.99 | -2.94 | 0.40 | -2.88 | 0.25 | -0.59 | -0.72* |
| R1 – R2 | -4.19 | 2.79 | -2.86 | -1.52 | -1.78 | -1.78 | 1.04* | -0.33 |

BF = barefoot; R0, R1, R2 = ski binding ramp angles of 0°, 1°, and 2°, respectively. AL,AM = perturbations occurring from the anterolateral and anteromedial directions, respectively.

* = Significant at $p < 0.05$

**FIGURES**

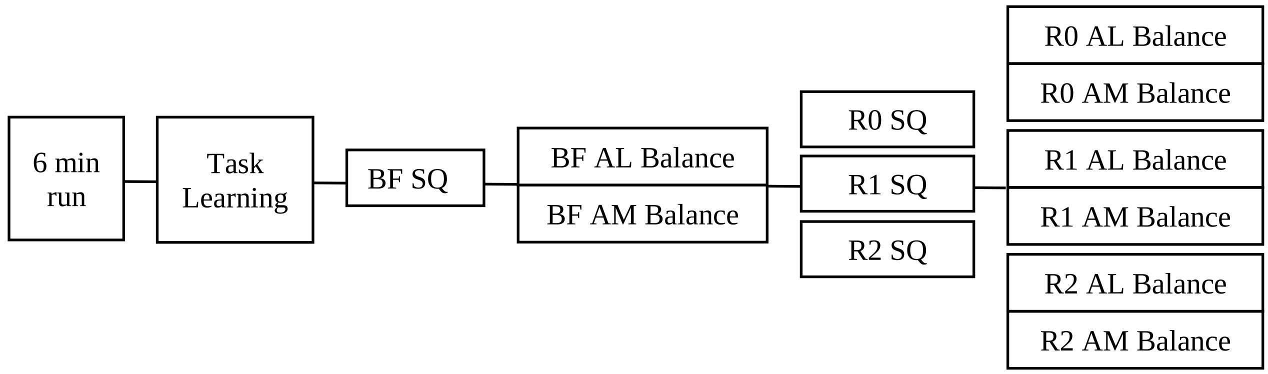
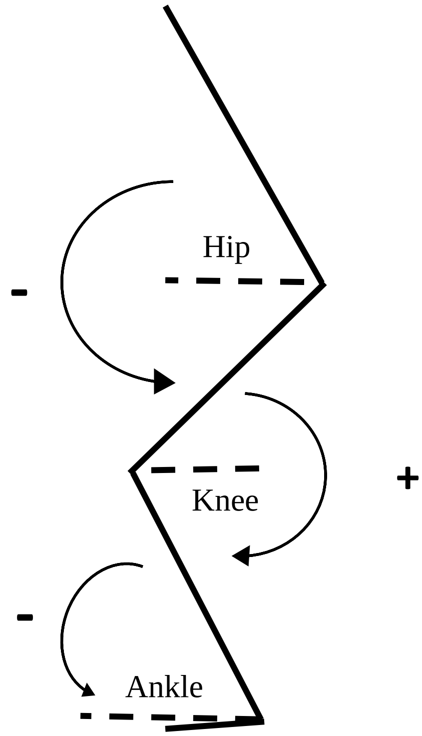



Figure 1 – Order of testing events.

The order of events involved in one testing session is shown. Ramp conditions were randomized and counterbalanced and an alternating pattern (by participant) was assumed with the order of anterolateral (AL) and anteromedial (AM) balance perturbations. R0, R1, R2 = ski binding ramp angle of 0°, 1°, 2°, respectively. SQ = squat.




Definitions of Joint Model

| | Knee Flexion | Coupling Phase | Interpretation | Knee Extension | Coupling Phase | Interpretation |
|---|---|---|---|---|---|---|
| Hip Flexion | ( − ) ( + ) | Antiphase | coordinated in flexion | ( − ) ( − ) | In-phase | opposing (uncoordinated) |
| Hip Extension | ( + ) ( + ) | In-phase | opposing (uncoordinated) | ( − ) ( + ) | Antiphase | coordinated in extension |
| Ankle Flexion | ( − ) ( + ) | Antiphase | coordinated in flexion | ( − ) ( − ) | In-phase | opposing (uncoordinated) |
| Ankle Extension | ( + ) ( + ) | In-phase | opposing (uncoordinated) | ( − ) ( + ) | Antiphase | coordinated in extension |

Figure 2 – Joint model and coupling phase definitions.

The direction of angular movement is defined in the relation to two moving segments: the hip angle is defined by the anatomical relationship of the torso to the thigh, the knee angle defined by the thighs to shank relationship, and the ankle is defined by the shank to foot relationship. The model and practical interpretation of coupling movement is included in the associated table, where the symbols (+) or (-) indicates the movement direction of one of the two joints being coupled.

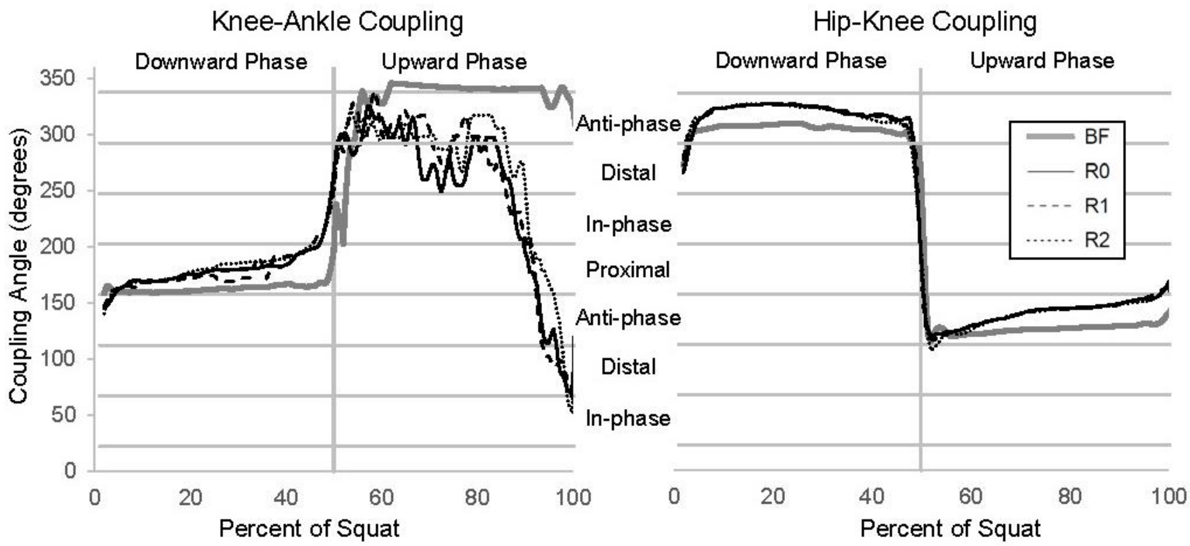



Figure 3 – Average coupling angles during squat tasks.

Average coupling angles of knee-ankle and hip-knee coordination during one squat are displayed for the non-dominant leg. The coupling pattern (movement driven by the distal joint, proximal joint, or in-phase/anti-phase joint contribution) is labelled for each angle range for which it is associated. Squat downward phase = 0 – 50%; upward phase = 51-100%. BF = barefoot; R0, R1, R2 = binding angles of 0°, 1°, and 2°, respectively.

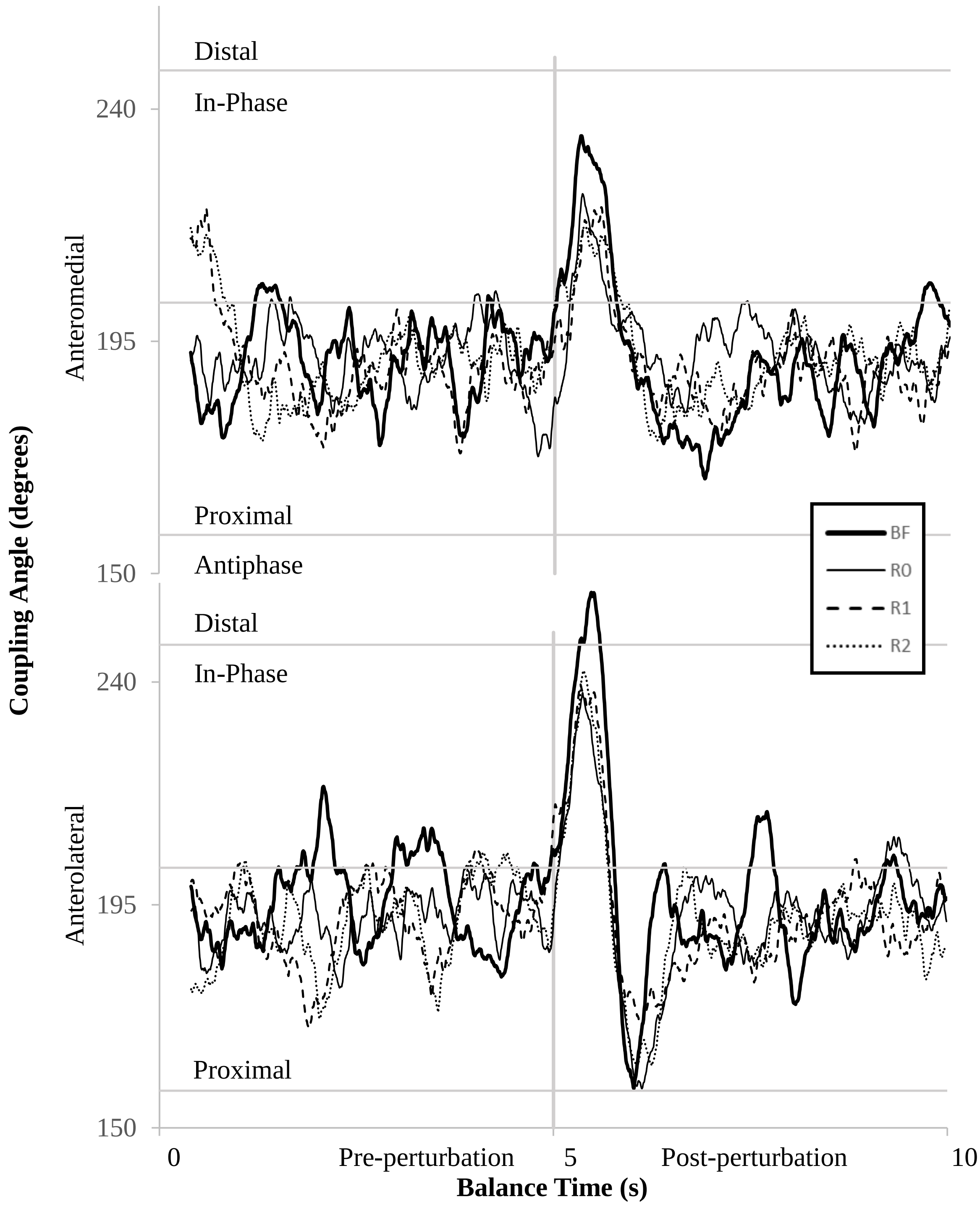



Figure 4 – Average hip-knee coupling angle during balance tasks.

Average hip-knee coupling angle is shown for four experimental conditions (BF = barefoot; R0, R1, R2 = ski binding angles of 0°, 1°, and 2°, respectively). The anteromedial (top) and anterolateral (bottom) perturbations are show separately. Significant differences exist between all ski conditions compared to the BF condition and between the two perturbation directions.

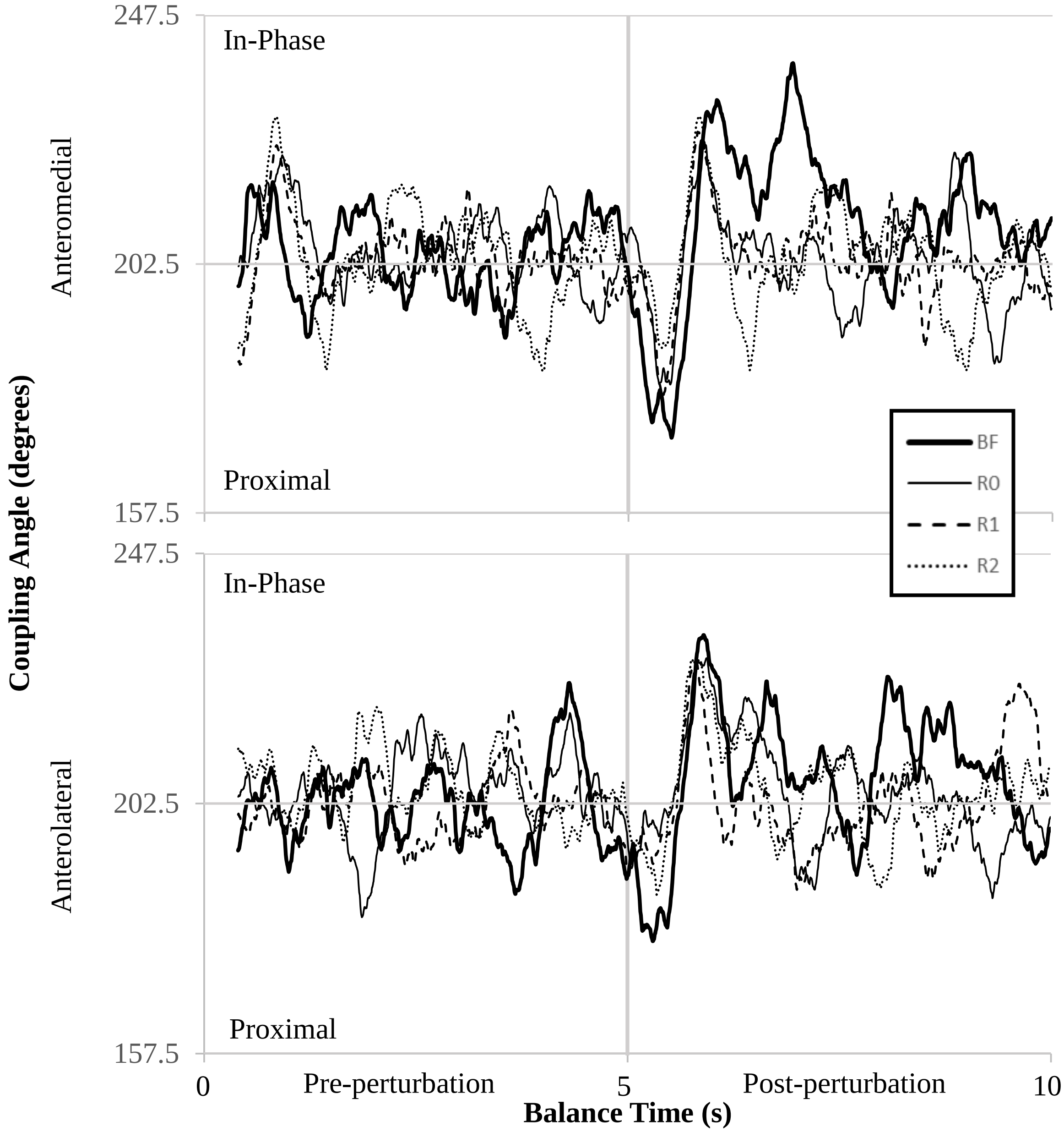



Figure 5 – Average knee-ankle coupling angle during balance task.

Average knee-ankle coupling angle is shown for four experimental conditions (BF = barefoot; R0, R1, R2 = ski binding angles of 0°, 1°, and 2°, respectively). The anteromedial (top) and anterolateral (bottom) perturbations are show separately. Significant differences exist between all ski conditions compared to the BF condition, R1 versus R2, and between the two perturbation directions.

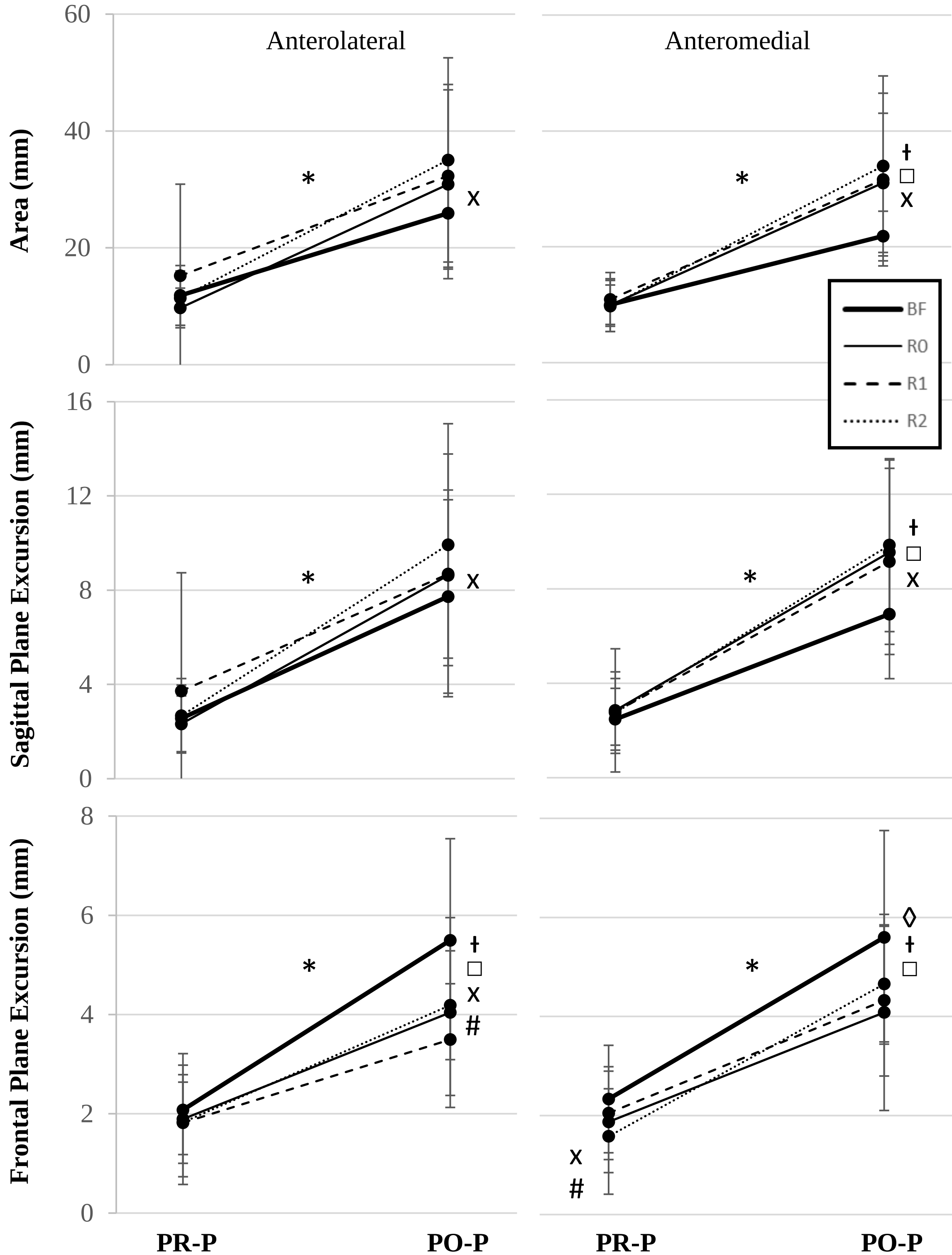



Figure 6 – Center of pressure interactions during balance tasks.

Center of pressure measures are presented pre-perturbation (PR-P) to post-perturbation (PO-P) for balance tasks with an anterolateral (left) and anteromedial (right) perturbation mechanism. BF = barefoot; R0, R1, R2 = ski binding angles of 0°, 1°, and 2°, respectively. Significance ($p < 0.05$): * = PR-P vs. PO-P, ƚ = BF vs. R0, □ = BF vs. R1, x = BF vs. R2, # = R1 vs. R2, ◊ = R0 vs. R2.

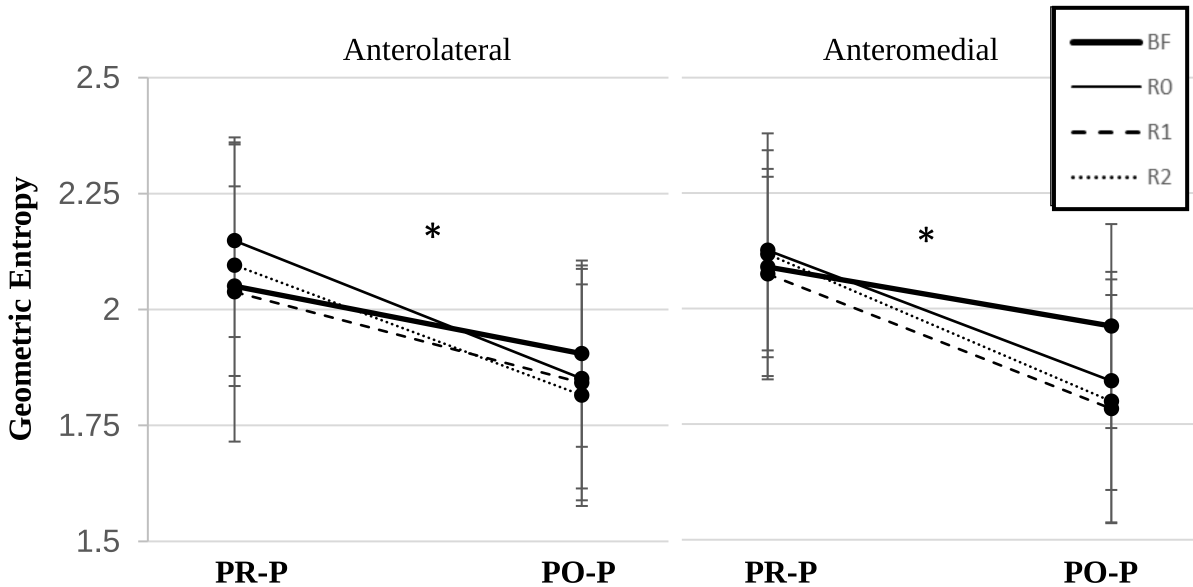



Figure 7 – Geometric entropy interactions during balance tasks.

Geometric entropy scores are presented pre-perturbation (PR-P) to post-perturbation (PO-P) for balance tasks with an anterolateral (left) and anteromedial (right) perturbation mechanism. The significant interaction between ramp and time is displayed in both graphs. BF = barefoot; R0, R1, R2 = ski binding angles of 0°, 1°, and 2°, respectively. Significance ($p < 0.05$): * = PR-P vs. PO-P.

## CHAPTER II: LITERATURE REVIEW

Alpine ski-essential equipment such as ski boots and ski bindings often create declining ramp angles from heel to toe, however these angles are not reported or regulated in the alpine ski industry. Korich (2016) reported that positive heel-to-toe heights occur in popular binding models and claimed that this will have significant effects on posture while skiing. Binding models from the 2011-2012 season increased heel heights substantially (Marker Baron binding = 0.60 mm; Head Mojo 7.5 = 9.0 mm; Rossignol SAS-110 binding = 10.0 mm) (Korich, 2016). Interestingly, these ramp angles and heel heights are not reported in the buyer's guides (Evo, 2017). Korich (2016) patented a toe-elevating binding to reduce these positive heel ramp angles, however in doing so contradicted a similar binding patent to increase the ramp angle from heel to toe by DeRocco and Higgins (1999). These patentees suggest that the positive angle will increase ankle flexion and thus the athletic posture of a skier. They further stated that females were more prone to un-athletic stances because they have larger hips and smaller upper bodies which inadvertently shifts their CoM to the rear (DeRocco & Higgins, 1999). However, the claims that ramp angles would influence the balance of a skier was not evidentially supported in either patent design.

### *Ski-Essential Equipment*

The modern ski boot creates a rigid sheath around the ankle and is important for applying pressure to the skis (Professional Ski Instructors of America, 2014). The rigid case restricts twisting and lateral forces of the ankle while allowing some fore-aft range of motion to be accomplished in ski boots; the skiers ability to flex the boot is dependent on body mass, boot resistance, speed, and skill level of the skier (Evo, 2017; Noé et al., 2009; Professional Ski Instructors of America, 2014). This ability to flex and extend the ankle is important to the maintenance of the CoM in relation to the base of support, thus having a profound effect on balance (Professional Ski Instructors of America, 2014).

The limited range of ankle flexion available in ski boots may affect the skier's ability to accomplish a dynamic, athletic stance (Professional Ski Instructors of America, 2014). In support of this, limiting dorsiflexion (accomplished by placing a twelve degree wedge under the forefoot to simulate a limited range of plantar flexion) is associated with decreased knee flexion and increased valgus during squat tasks (Macrum et al., 2012). Dill, Begalle, Frank, Zinder, and Padua (2014) approached the same research question from the opposite angle, finding that increased range of motion in the ankle (specifically dorsiflexion) was associated with greater knee flexion during squat tasks. However, when applied to more dynamic jump landings, this finding was not upheld (Dill et al., 2014). Thus, the similarly dynamic nature of ski tasks makes the resulting knee range of motion ambiguously applicable to the effects of ski boot restrictions. In fact, Noé et al. (2009) studied experienced alpine skiers during balance tasks (booted and unshod, with visual feedback and with eyes closed, and with stability board motion) and found that participants performed similarly between conditions because they exploited the mechanical support of the ski boot by modifying muscle recruitment patterns. This pattern modification may affect less experienced skiers differently. However, regardless of experience, a skier's maintenance of balance is inherently different in ski boots than tasks of typical daily movement.

*Ski Balance Task Performance*

Skiers' balance task performance has been studied inconsistently, without employing normative methods. While some examined balance tasks after a period of ski training (Mildner et al., 2010; Noe, 2005; Wojtyczek, Pasławska, & Raschner, 2014), others investigated balance in ski boots (Koyanagi et al., 2005; Noé et al., 2009, 2018; Panjan et al., 2016), though none of these investigated static balance on the full ski. Because athletes have a higher degree of motor expertise and postural ability than non-sportspeople, Mancini and Horak (2010) suggest that static posturography can be made more difficult by decreasing the area of the base of support, visual feedback, proprioceptive feedback, or by applying a secondary task. There is a possibility that previous researchers didn't want to employ a larger base of support by studying participants on skis, because the challenge of the test would be attenuated.

Similar to the equipment used during experimental protocols, the qualitative results of balance tasks are also inconsistent. According to Bennell and Goldie (1994), balance task performance and postural control decreases with higher levels of ankle support, implying that a similar consequence should occur from practice in ski boots due to the high level of ankle restriction involved. However, Noé et al. (2009) found that experienced alpine skiers maintained balance task performance while wearing ski boots. Instead of a compromised balance from the restricted range of motion at the ankle joint, skiers exploited the mechanical support of the boots with muscle recruitment pattern modifications (Noé et al., 2009). This suggests that the stabilizing feedback of the ankles is not a limitation in ski boots because the body's redundancies can accommodate balance challenges even though only slight ankle movement is available. Further, Noé, García-Massó, Delaygue, Melon, and Paillard, (2018) found that the use of rigid and soft boots (flex index equal to 120 and 70, respectively) increased active postural control when challenged in the mediolateral direction. Interestingly, decreased active postural control was seen with a rigid boot when an anteroposterior balance challenge was introduced. Further, beginner skiers who were posturally unaccustomed to the mechanical support of a ski boot showed worse stability (area and stability index) in the sagittal plane compared to when the skiers were barefoot (Tchórzewski et al., 2013).

Conversely, Noe (2005) discovered that regional level skiers displayed better out-of-boot postural control than national level skiers, suggesting that perhaps the national skiers were more accustomed to the limitations of ski boots. However, skiers (skill defined as "experienced") improved out-of-boot balance task performance after six weeks ski training (Wojtyczek et al., 2014). In studying a comparatively older population, Müller et al. (2011) found no significant changes in balance after a twelve week ski intervention. In ski boot balance tasks, unsurprisingly, trained skiers performed better at balance task performance than untrained (Panjan et al., 2016). These studies may have inconsistent results because of the widespread variety of balance task methods used in sport and clinical practices. Additionally, inherent differences between sports that practice on stable and unstable surfaces may affect the success of athletes in standard tasks. According to Powell and Williams (2015), an anticipatory feedback mechanism is employed more during sports performed on unstable surfaces than stable ones. These differences may affect the strategy to which athletes in skis recover equilibrium and thus may require more challenging and ski-specific balance tasks to demonstrate their sport-specific motor control.

*Ski Specific Postural Stability*

Skiers utilize sensory feedback in both anticipatory and compensatory mechanisms; making the combination of necessary balance adjustments and the cognitive decisions necessary for dynamic skiing, a highly integrative task (Hébert-Losier et al., 2014; Louis et al., 2012). Hébert-Losier et al. (2014) provide some examples of the judgements skiers face including the radius and trajectory of the turn, inclination angle of skis, timing of joint motions, and the pressure applied from the ski to the snow. Finite performance decisions such as the pressure distribution on the ski can greatly affect the interaction of the skis with the snow (Powell &

Williams, 2015). The amount, location, and direction of pressure application can affect the speed of ski translation across the snow (Powell & Williams, 2015; Professional Ski Instructors of America, 2014). This translation-causing pressure is measured by the amount and location of ground reaction forces (GRF); and improper timing and magnitude of these forces significantly affect balance maintenance (Hébert-Losier et al., 2014; Panjan et al., 2016; Professional Ski Instructors of America, 2014).

Biomechanical adjustments can be made to either maintain, achieve, or restore postural equilibrium while skiing (Mancini & Horak, 2010). Paillard (2017) describes postural modifications as either anticipatory or compensatory; whereas balance can be preserved by making adjustments prior to, during, or after a balance disturbance (Figure 8). The anticipatory system is accomplished through a feed-forward mechanism, whereas the compensation system is accomplished via a feedback mechanism from the sensory system (Paillard, 2017). Specifically,

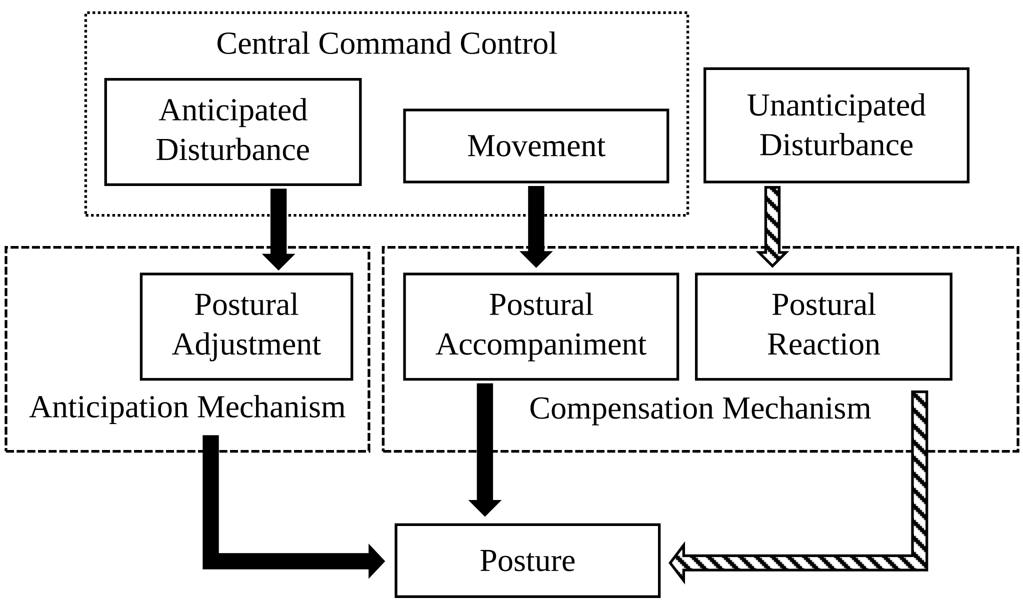



Figure 8 – Postural control mechanisms.

Postural control is accomplished through both anticipation and compensation mechanisms. Balance can be preserved by making adjustments prior to or during/after a disturbance. The compensation mechanism acts through a feedback system whereas the anticipation mechanism acts in a feedforward fashion. Adapted from *Plasticity of the postural function to sport and/or motor experience* by Thierry Paillard, 2016.

the physiological systems integrated into this feedback are the vestibular, visual, proprioceptive, muscular, and reactive time (ability to send and translate signals) (Mancini & Horak, 2010). Thus, a great degree of system integration is necessary for optimal performance in the sport.

According to teaching guidelines of Professional Ski Instructors of America (2014), balance maintenance and posture play an important role in a skier's dynamic response to terrain changes and the prevention of falls. The "gold standard" posture in recreational skiing is one that employs an athletic stance, defined as "the ability of an athlete to move in any direction at any time" (Professional Ski Instructors of America, 2014, p. 33). This dynamic capability is essential for the skier's response to terrain inconsistencies (Panjan et al., 2016; Powell & Williams, 2015; Professional Ski Instructors of America, 2014). An athletic stance is accomplished with fluid and reactive ankle, knee, and hip flexion during a dynamic turn, with the maintenance of a neutral pelvis (Professional Ski Instructors of America, 2014). Fundamental skills required to accomplish an athletic stance and reduce the risk of falling are edging (the angle skis cut into the snow), rotation of the skis, balance maintenance, and pressure control of skis over the snow (Professional Ski Instructors of America, 2014).

Common postural errors associated with the reduction of balance occur from improper maintenance of the center of mass in relation to the base of support (Winter, 1995). The reduction of an athletic stance in skiing is associated with improper ankle, knee, and/or hip joint angles, creating an anterior or posteriorly shifted CoM (Professional Ski Instructors of America, 2014). Excess ankle flexion can result in an anterior CoM (and thus, CoP) on the skis, while excess extension can result in a posterior CoP (Professional Ski Instructors of America, 2014). The magnitude of the pressure on the front of the ski can also be increased by knee extension or hip flexion (Figure 9), whereas pressure on the tails of the skis can be applied by knee and hip flexion (as if the athlete were about to sit back into a chair) (Professional Ski Instructors of America, 2014).

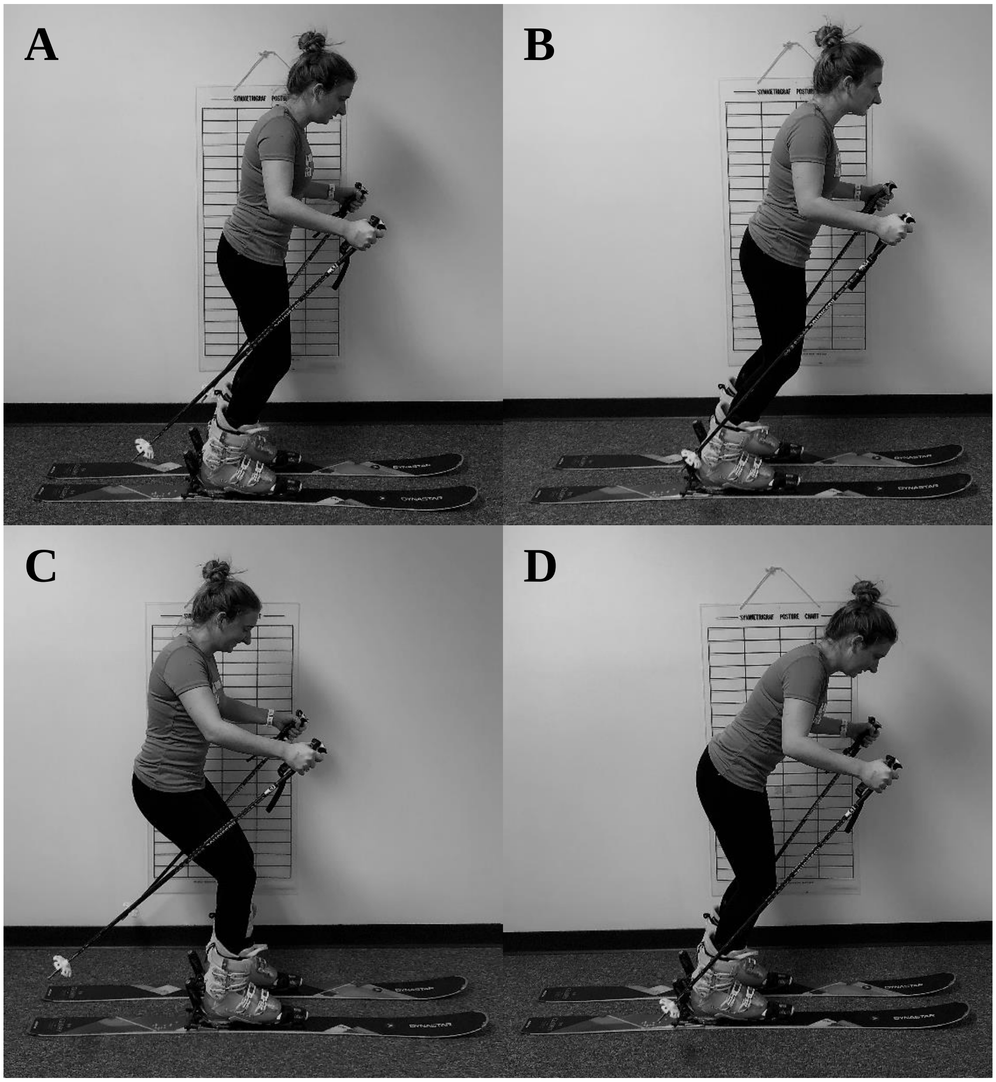



Figure 9 – Ski-specific joint relationship examples.

A. Proper athletic stance in skiing aligns the center of mass above the base of support, B. An anteriorly shifted center of mass is displayed with ankle flexion and knee extension, creating an anterior pressure on the skis, C. . “Back seat” skiing or backward bending is demonstrated, posteriorly pressuring the skis with knee and hip flexion, D. Anterior pressure on the ski is accomplished through hip flexion. Adapted from Alpine Technical Manual, by Professional Ski Instructors of America, 2014. Copyright 2014, by the American Snowsports Association, Inc.

Balance control has been linked to expertise in sport because of the increased level of neuromuscular control that influences posture (Paillard, 2017). This motor control may be influenced by leg dominance, aging, neuropathy, and/or the level of training (Bennell & Goldie, 1994; Mancini & Horak, 2010; Paillard, 2017; Prieto et al., 1996). Improper neuromuscular control and the balance of musculature can contribute to the risk of injury in sports (Hewett, Myer, & Ford, 2006). Specific to skiing, Müller and Schwameder (2003) studied skier biomechanics during new-age carving and parallel turns, finding that in both turn styles, an up-unweighting motion helped to initiate the turn. In Müller and Schwameder's (2003) biomechanical analysis, the up-unweighting was primarily accomplished through extension of the knee. Similarly, at the initiation of a parallel turn, extension and unweighting in both legs happens at the same time in expert skiers; whereas less experienced skiers tend to start this phase nearly extended, allowing for less of an extension movement at turn initiation (Müller et al., 1998). According to the Professional Ski Instructors of America (2014), the up-unweighting motion reduces the pressure applied from the ski to the snow and allows the skier to rotate the skis. Thus, the pressure application from the skier to the skis is affected by the turn mechanics, as well as the expertise of the skier. Ultimately, inexperience and improper or untrained neuromuscular function can contribute to incorrect postures resulting in a less than ideal pressure distribution across the skis.

*Negative Ramp Angles*

Patent holders of ramp angles created by the ski binding complex suggest that the joint adaptations elicited by the equipment may in fact improve some of the improper postures adopted by recreational skiers (DeRocco & Higgins, 1999). Although research on the postural effects of ramp angles have not been adequately researched in ski tasks, similar dual leg tasks may provide insight into their consequences. Evidence suggests that a similar ramp angle applied in weight lifting shoes decreases the lateral displacement of the hip during squats and reduces the forward lean of the trunk (Legg et al., 2017; Sato et al., 2012). This reduction of forward lean reduces shear forces on intervertebral disks in the low back, however, these studies also found an increase in knee extensor activity and moments (Hartmann et al., 2013; D. Lee et al., 2015; Legg et al., 2017; Sato et al., 2012). Increased knee flexion is associated with the available range of dorsiflexion as evidenced in participants that performed squats and jump landing tasks with limited dorsiflexion range of motion or weight lifting shoes (Dill et al., 2014; Legg et al., 2017; Macrum et al., 2012). Although this knee range of motion may be a benefit of using weight lifting shoes, large changes in the dorsiflexion range of motion will likely be restricted by the sheath-like nature of a ski boot.

D. Lee, Lee, & Park (2015) hypothesized that increased rectus femoris activation during squats performed on a decline of 25° was seen due to a compensatory backward lean, resulting from participants resisting the feeling of falling forward. In a similar suggestion, Fortin, Harrington, and Langenbeck (1997) claimed that figure skates that instigate 15˚ of plantar flexion may also prompt "genu recurvatum" to shift the CoM backward as a compensation of the forward nature of the skate. These claims can be supported in a similar application; standing and walking in high heels (4.5-8 cm), creating an increased lumbar flexion angle (posterior shift), unstable posture, and posterior CoM movement (C.-M. Lee et al., 2001). The posterior shifting of the trunk as seen in high heeled walking was also seen via a posterior pelvic tilt when participants walked downhill (Hong et al., 2014). These posterior adaptations would be counterproductive to the joint relationships needed to implement a ready, athletic stance in skiing. Similar to weight lifting shoe conditions, walking in high heels elicited increased knee extensor moments (Esenyel et al., 2003; Ho et al., 2012; Kuster et al., 1994). If similar joint mechanics and biomechanical adaptations are manifested during downhill ski tasks, the orientation of the binding plate may result in altered balance and posture of an alpine skier.

During giant slalom turns, Kröll et al. (2006) found that increasing the ramp angle of the bindings resulted in a greater forefoot pressure loading and run times. These researchers did not measure the accompanying angular kinematics, however, changes in pressure distribution may challenge the skier's ability to maintain their postural equilibrium and thus affect their coordination patterns. For example, after fatiguing lifting tasks, changes in joint coordination were found in conjunction with increased anterior-to-posterior CoM excursion (Sparto et al., 1997). Similarly, in ski boot balance tasks, Tchórzewski, Bujas, and Jankowicz-Szymańska (2013) suggested that the differences they measured in sagittal plane stability indices in beginner alpine skiers were due to changes in muscular coordination via an increased strategy of the hip joint. Ultimately, the effects of the boot-binding complex may increase the difficulty of preserving postural equilibrium during skiing because of the joint restrictions of the boot and orientation of the binding. It is thus imperative to investigate the changes in balance and coordination due to the binding ramp angle in ski-specific tasks.

# CHAPTER III: CONCLUSIONS AND RECOMMENDATIONS

Significant differences in the coordinative patterns and center of pressure excursions that occur from the addition of a ski boot-binding complex may affect the performance of recreational alpine skiers. Uncoordinated movements that occur at the top and bottom of the ski range of motion may subsequently affect the ability of the skier to properly translate and rotate the ski during parallel turns. Further, greater CoP area and excursions are associated with ski conditions, along with greater knee contribution to movement. Skiers should thus be aware of increased balance challenge that is elicited by the addition of the ski boot and binding complex.

Varying degrees of ramp angles created by ski bindings are associated with alterations in dynamic joint coordination that do not coincide with alterations in CoP sagittal plane excursion and area. Although the coordinative pattern appears to trend toward the native pattern with the highest ramp angle, this is not notably beneficial when assessing the CoP measurements. In fact, when balance task performance was assessed across conditions, the highest degree of ramp indicated greater excursions and area than BF conditions (when R0 and R1 *sometimes* did). Thus, recreational alpine skiers are recommended to apply a binding with more modest ramp conditions, as the current study suggests a greater balance challenge associated with higher ramp angles.

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# APPENDIX A

## NORTHERN MICHIGAN UNIVERSITY
## SCHOOL of HEALTH & HUMAN PERFORMANCE

## CONSENT TO ACT AS A HUMAN SUBJECT

Thank you for your interest in participating in this research study. The purpose of this study is to investigate the biomechanical effects of increasing the ramp angles of ski bindings.

You are invited into this study because you are either a member of the Marquette, Salzburg, NMU, or University of Salzburg communities and enjoy recreational skiing as a hobby. Additional information is needed about your ski experience before enrollment in this research study. If you have not filled out a Ski History Questionnaire, please request one from Stephanie Moore before continuing this form.

If you agree to participate and have already filled out a Ski History Questionnaire, please acknowledge the following:

> As a participant in this study, I ___________________________________ understand that I will be asked to partake in repeated balance tasks and light physical activity. I understand that I will be asked not to exercise intensely 24 hours prior to the scheduled test, and refrain from alcohol, pharmaceutical and recreational drugs that may affect balance for 24 hours prior to testing.
>
> I realize that measurements of my height, weight and boot size will be recorded. I am aware that these measurements are used in the effort to analyze individual balance on skis. I am also aware that motion capture and force measurements will be taken in 3 conditions: 1. A one legged ski balance with perturbation and a ramp angle of 0°; 2. Condition 1 with a ramp angle of 1.0°; 3. Condition 2 with a ramp angle of 2.0°. In each of these conditions, my balance will be perturbed three times each, from the anterior (front), left anterolateral and right anterolateral direction. I understand this means for each leg, 27 balance perturbation tasks will be performed. I realize that video will be recorded of my performance during the tasks, however, this video will not be accessed by anyone other than the test administrators.
>
> I understand that in order to accurately place motion capture markers, I must wear appropriate ski base layer attire, consisting of spandex shorts, capris, or pants, as well as a tank top or tight-fitting spandex shirt. Ski socks that reach above boot height will also be necessary for me to wear to the testing session. I also understand I need to wear athletic shoes for a light, 5 min, cycle ergometer warm-up.

I recognize that I am free to ask questions at any time about any of the tests performed during this study. If for any reason I am unable to perform a given test, I will inform the researcher. Because my health status can directly affect my safety during exercise, I will disclose any foreseen health problems to the researcher and fill out the next page (PAR-Q) with all honesty. I will also promptly report any feelings of discomfort or pain if they occur before, during, or after a given test to one of the researchers.

Information will not be disclosed to anyone other than the researchers unless additional written consent is given. However, federal regulatory agencies and the Northern Michigan University Institutional Review Board (a committee that reviews and approves research studies) may inspect and copy records pertaining to this research. Otherwise, I understand that my information will be held in confidentiality.

I will not have to personally fund my participation in this study, except for transportation to the laboratory testing session in my respective city. I will not receive individual compensation for my participation, though myself and others may benefit in the future from what is learned as a result of this study.

My enrollment and consent to participate in this study is voluntary and I realize that I am free to withdraw from any test, at any time, for any reason (disclosed or undisclosed). If I have further questions regarding my rights as a participant in a research project I may contact Dr. Lisa Schade Eckert, Interim Assistant Provost of Graduate Education/Research of Northern Michigan University at (906-227-2300) or leckert@nmu.edu. Additionally, if I have any questions regarding the study, I understand I am free to contact the principle researchers, Stephanie Moore (425-293-7595 or stepmoor@nmu.edu) and Dr. Randall Jensen (906-227-1184 or rajensen@nmu.edu) at any time.

If you have read this form and agree to volunteer your participation in this experiment, please sign below to signify your informed consent of procedures, risks, expectations and participant rights.

________________________________ ________________________________

Signature of Volunteer Date

________________________________ ________________________________

Signature of Witness Date

## APPENDIX B

Physical Activity Readiness Questionnaire - PAR-Q (revised 2002)

# PAR-Q & YOU

**(A Questionnaire for People Aged 15 to 69)**

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

| YES | NO | | |
|---|---|---|---|
| ☐ | ☐ | 1. | **Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?** |
| ☐ | ☐ | 2. | **Do you feel pain in your chest when you do physical activity?** |
| ☐ | ☐ | 3. | **In the past month, have you had chest pain when you were not doing physical activity?** |
| ☐ | ☐ | 4. | **Do you lose your balance because of dizziness or do you ever lose consciousness?** |
| ☐ | ☐ | 5. | **Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?** |
| ☐ | ☐ | 6. | **Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?** |
| ☐ | ☐ | 7. | **Do you know of any other reason why you should not do physical activity?** |

## If you answered

### YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

### NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

**DELAY BECOMING MUCH MORE ACTIVE:**

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

**PLEASE NOTE:** If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

**No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.**

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ________________________________________

SIGNATURE ________________________________ DATE ________________________

SIGNATURE OF PARENT ______________________ WITNESS ________________________
or GUARDIAN (for participants under the age of majority)

**Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.**



continued on other side...

# APPENDIX C

**Ski History Questionnaire (SH-Q)**

**Name** ___________________________ **Sex (circle one):**

**Age** ___________ Male Female

***Please ask the questionnaire administrator if you have any clarification questions.***

**Circle any of the following that you have experienced in the past 3 years.**

Lower limb injury

Chronic low back pain

Lower limb ligament tear/rupture

Lower limb ligament reconstruction

Lower limb/foot fractures

**Circle any of the following that applies to you now.**

Lower limb deformation

Vestibular disorder

Neurological disorder

Difficulty balancing during every day activities

Use of pharmacological or recreational drugs

**Have you ever been injured while alpine skiing?**

Yes If Yes, what age? ______ Please explain location and injury:

No

**What type of skier would you consider yourself? (Choose only one, mark with an X)**

_____ Type 0 (pure beginner)

_____ Type 1 (ski conservatively, prefer lower speeds, moderate to easy terrain)

_____ Type 2 (ski moderately, prefer a variety of speeds, ski on varied terrain including most difficult)

_____ Type 3 (ski aggressively, normally ski at high speeds, prefer steeper & more challenging terrain)

_____ Type 3+ (ski racer/instructor/professional)

**How many seasons (10+ days) of alpine ski experience have you had? (Need not be consecutive)**

0 1 2 3 4 5 6 8 9+

**How many days per season would you estimate you skied in the last 3 consecutive seasons of skiing?**

_________/_________/_________

(Most recent → 3 years ago)

**Have you ever had formal ski lessons or instruction?**

Yes, within the last 3 years

Yes, when I was young

No

**Do you own your own ski boots?**

Yes If yes, do you know the flex rating on the boot? ________________

No If yes, what is the brand/model? ____________________________

**The majority (60%+) of your ski day is spent on runs that are....**

Green Blue Black Double Black

**How would you describe your skis during a turn?**

Plough (Pizza) Semi-Parallel Always Parallel On corresponding edges

**How often do you fall on skis?**

Every run Every day Now and then Rarely, if ever

**Please rate the challenge you experience when skiing each of the following run types:**

***Green, beginner hill***

Easy Moderate Difficult Never Again No Experience

***Green, groomed***

Easy Moderate Difficult Never Again No Experience

***Blue, groomed***

Easy Moderate Difficult Never Again No Experience

***Blue, off-piste (non-groomed)***

Easy Moderate Difficult Never Again No Experience

***Black, groomed***

Easy Moderate Difficult Never Again No Experience

***Black, off-piste (non-groomed)***

Easy Moderate Difficult Never Again No Experience

***Double Black***

Easy Moderate Difficult Never Again No Experience

***Moguls***

Easy Moderate Difficult Never Again No Experience

***Glades***

Easy Moderate Difficult Never Again No Experience

***Ice***

Easy Moderate Difficult Never Again No Experience

***Exposed, steep***

Easy Moderate Difficult Never Again No Experience

***Narrow, steep (chute)***

Easy Moderate Difficult Never Again No Experience

***Avalanche terrain***

Easy Moderate Difficult Never Again No Experience

***Cliffs***

Easy Moderate Difficult Never Again No Experience

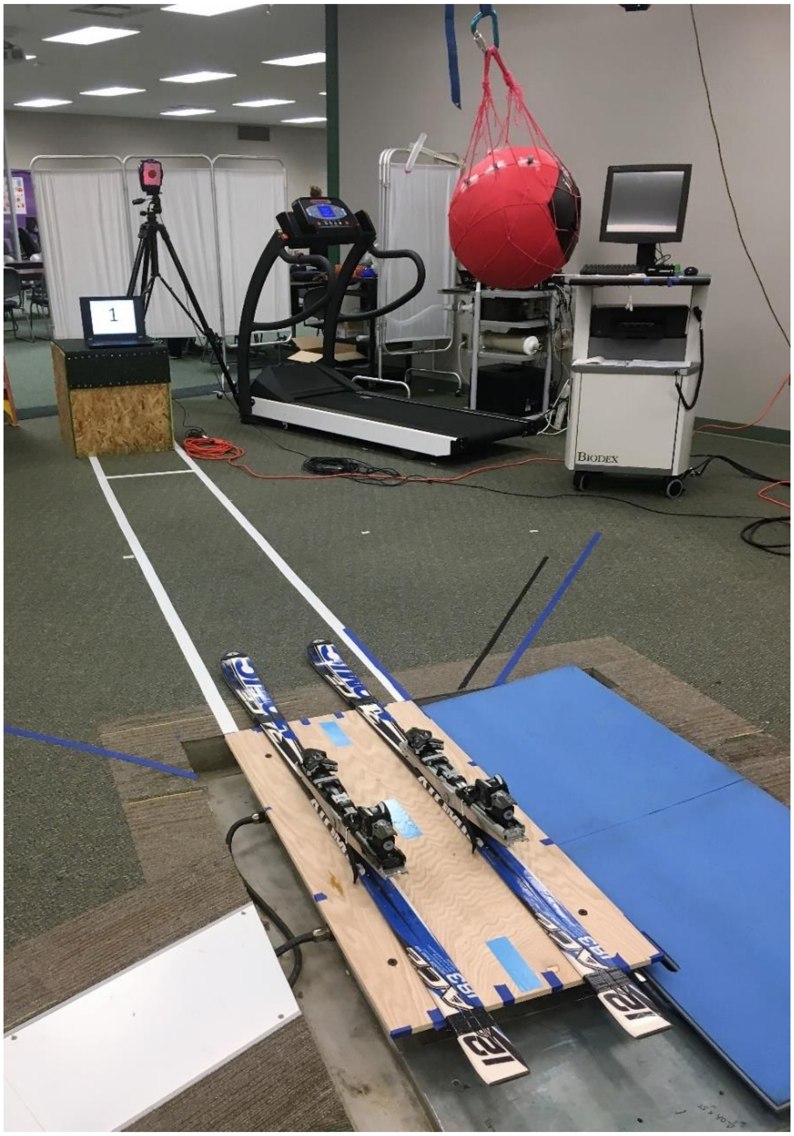
***Terrain park***

Easy Moderate Difficult Never Again No Experience

**Please rank yourself on your ski ability:**

Beginner Intermediate Advanced Expert

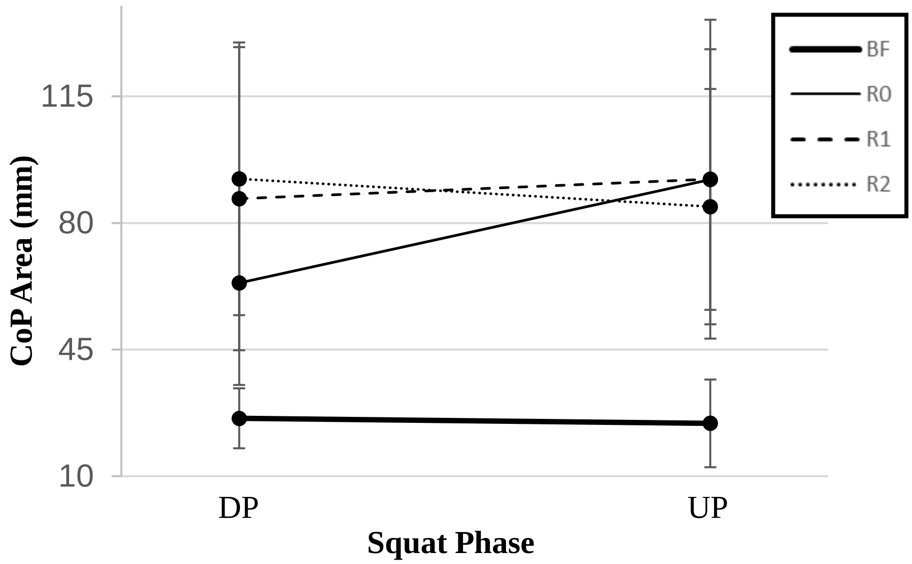
## APPENDIX D




Appendix D: Picture of example test set-up.

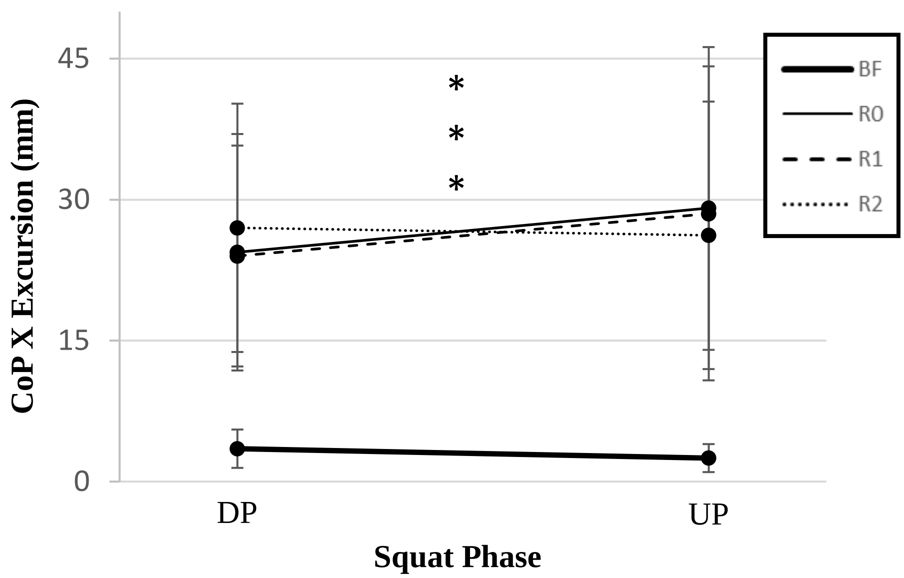
The laboratory set up is shown for the squat tasks. The entire ski does not touch the ground surface, instead the wooden surface (length = 1.2 m) was used to normalize the contact area of the skis in each of the testing laboratories. Additionally, the balance perturbation mechanism (medicine ball pendulum) can be seen along with the location of the anteriorly located randomized number slideshow.

## APPENDIX E



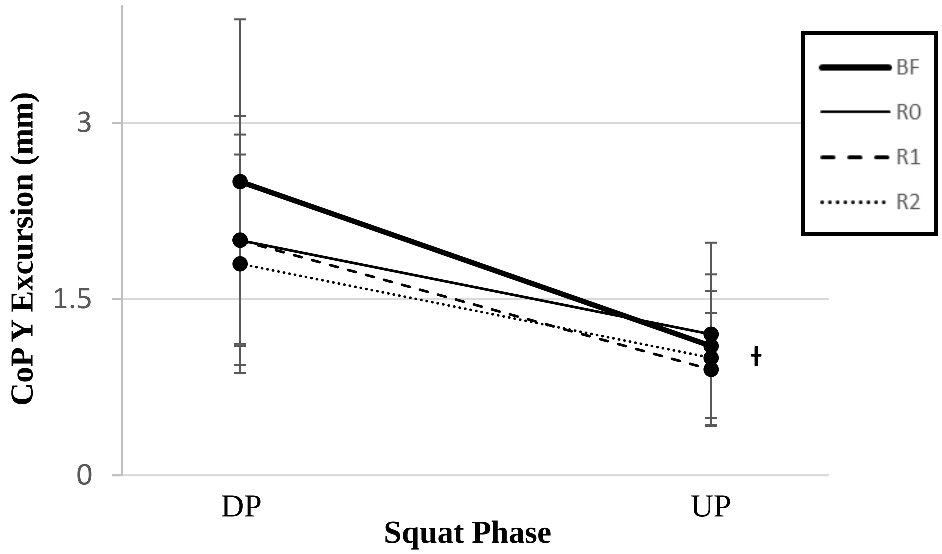

Appendix E: Figure 10 - CoP area during squat tasks.

Center of pressure excursion in the sagittal plane (X) for both the down phase (DP) and up phase (UP) is displayed for four experimental conditions (BF = barefoot; R0, R1, R2 = ski binding angles of 0°, 1°, and 2°, respectively).
* indicates the condition significantly differs from BF condition.



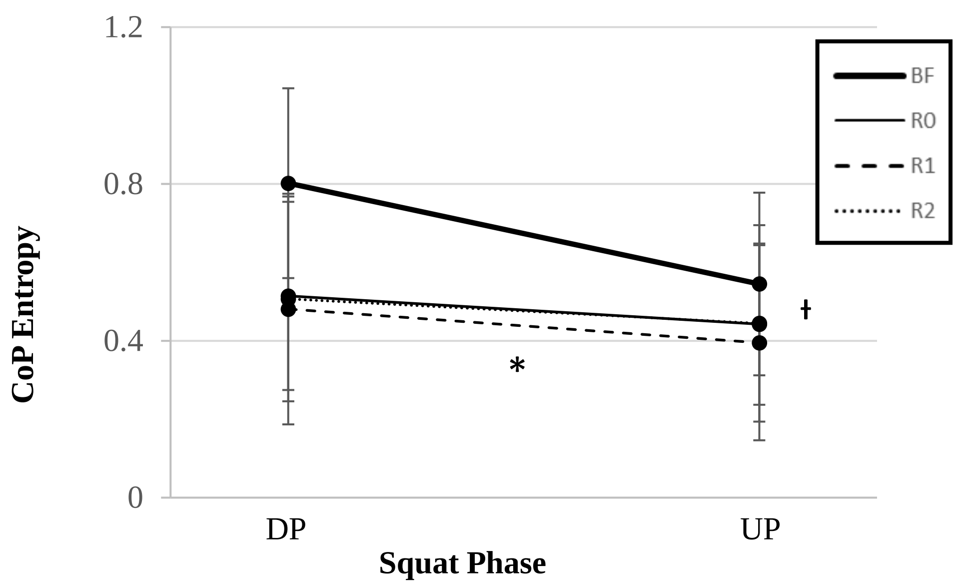

Appendix E: Figure 11 – Sagittal plane CoP excursion during squat tasks.

Center of pressure excursion in the sagittal plane (X) for both the down phase (DP) and up phase (UP) is displayed for four experimental conditions (BF = barefoot; R0, R1, R2 = ski binding angles of 0°, 1°, and 2°, respectively). * indicates the condition significantly differs from BF condition.




Appendix E: Figure 12 – Frontal plane CoP excursion during squat tasks.

Center of pressure excursion in the frontal plane (Y) for both the down phase (DP) and up phase (UP) are displayed for four experimental conditions (BF = barefoot; R0, R1, R2 = ski binding angles of 0°, 1°, and 2°, respectively). ƚ indicates significant differences between phases were observed.




Appendix E: Figure 13 – CoP entropy during squat tasks.

Average center of pressure entropy for both the down phase (DP) and up phase (UP) are displayed for four experimental conditions (BF = barefoot; R0, R1, R2 = ski binding angles of 0°, 1°, and 2°, respectively). A significant ramp vs. phase interaction likely occurs from the BF condition. * indicates the condition (R1) significantly differs from BF condition. ƚ indicates significant differences between phases were observed.

# APPENDIX F

Appendix F: Table 7 – Hip-knee coupling frequencies during ski balance tasks.

| | Hip – Knee Coupling | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Pre-perturbation | | | | Post-perturbation | | | |
| **AL** | **BF** | **R0** | **R1** | **R2** | **BF** | **R0** | **R1** | **R2** |
| Hip | 13.4 ± 4.4 | 16.3 ± 6.5* | 16.1 ± 6.4* | 15.6 ± 5.4* | 13.3 ± 4.6 | 16.2 ± 5.7* | 16.4 ± 5.9* | 15.2 ± 5.1* |
| Knee | 34.1 ± 6.8 | 31.4 ± 6.8 | 32.7 ± 10.2 | 32.3 ± 10.6 | 34.3 ± 10.5 | 32.8 ± 10.0 | 31.8 ± 10.3 | 31.9 ± 8.0 |
| In | 12.2 ± 4.3 | 13.3 ± 2.6 | 13.9 ± 3.1 | 12.7 ± 3.6 | 11.4 ± 3.1 | 13.2 ± 3.1 | 13.8 ± 2.9 | 13.1 ± 3.1 |
| Anti | 40.1 ± 12.4 | 38.9 ± 6.3 | 37.3 ± 9.4 | 39.3 ± 11.5 | 40.9 ± 9.3 | 37.8 ± 9.1 | 38.0 ± 8.7 | 39.7 ± 7.7 |
| **AM** | **BF** | **R0** | **R1** | **R2** | **BF** | **R0** | **R1** | **R2** |
| Hip | 12.0 ± 3.4 | 13.9 ± 3.7* | 15.2 ± 4.7* | 16.7 ± 4.9* | 13.5 ± 4.0 | 15.5 ± 4.6* | 16.6 ± 6.6* | 15.2 ± 4.6* |
| Knee | 39.2 ± 14.1 | 35.2 ± 9.9 | 31.3 ± 9.3 | 32.3 ± 8.7 | 36.3 ± 7.8 | 33.6 ± 10.3 | 33.6 ± 10.8 | 34.5 ± 8.8 |
| In | 13.1 ± 3.9 | 12.3 ± 3.1 | 13.5 ± 3.3 | 13.1 ± 2.7 | 12.9 ± 3.3 | 14.3 ± 4.1 | 13.7 ± 3.0 | 13.9 ± 2.9 |
| Anti | 35.5 ± 13.0 | 38.5 ± 9.2 | 39.9 ± 10.3 | 37.9 ± 7.8 | 37.2 ± 8.1 | 36.6 ± 10.0 | 36.1 ± 7.7 | 36.4 ± 6.7 |

* = significantly different from BF condition ($p < 0.05$)
AL, AM = Direction of perturbation mechanism, anterolateral and anteromedial, respectively.
BF = barefoot, R0, R1, R2 = ski binding ramp angles of 0°, 1°, and 2°, respectively.

Appendix F: Table 8 – Knee-ankle coupling frequencies during ski balance tasks.

| | Knee - Ankle Coupling | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Pre-perturbation | | | | Post-perturbation | | | |
| **AL** | **BF** | **R0** | **R1** | **R2** | **BF** | **R0** | **R1** | **R2** |
| Knee | 34.5 ± 11.5 | 27.4 ± 6.7* | 26.1 ± 8.3* | 27.1 ± 11.6* | 35.1 ± 9.7 | 26.7 ± 8.5* | 28.4 ± 7.3* | 29.3 ± 7.5* |
| Ankle | 11.9 ± 4.4 | 13.0 ± 3.7 | 13.9 ± 3.7 | 12.7 ± 4.5 | 11.1 ± 3.6 | 13.3 ± 4.3 | 13.0 ± 3.2 | 12.4 ± 3.6 |
| In | 10.3 ± 3.2 | 10.8 ± 4.1 | 11.8 ± 4.3 | 10.5 ± 2.9 | 10.8 ± 2.8 | 11.4 ± 3.7 | 11.2 ± 4.4 | 10.9 ± 4.1 |
| Anti | 43.5 ± 12.8 | 48.2 ± 8.5 | 47.4 ± 11.1 | 49.1 ± 12.6 | 42.9 ± 10.2 | 48.3 ± 10.9 | 46.8 ± 11.3 | 46.9 ± 11.0 |
| **AM** | **BF** | **R0** | **R1** | **R2** | **BF** | **R0** | **R1** | **R2** |
| Knee | 30.4 ± 11.3 | 27.6 ± 8.8* | 27.9 ± 9.2* | 26.0 ± 7.9* | 33.5 ± 9.5 | 28.3 ± 10.0* | 26.9 ± 8.5* | 25.1 ± 6.5* |
| Ankle | 11.6 ± 3.8 | 12.1 ± 3.4 | 12.8 ± 2.8 | 13.2 ± 4.2 | 11.7 ± 4.1 | 11.9 ± 3.2 | 13.0 ± 3.9 | 12.9 ± 2.4 |
| In | 9.5 ± 3.1 | 10.4 ± 5.2 | 11.2 ± 3.6 | 11.6 ± 4.1 | 9.4 ± 2.2 | 10.3 ± 2.8 | 10.9 ± 3.5 | 11.2 ± 4.4 |
| Anti | 48.4 ± 12.2 | 49.4 ± 12.5 | 47.6 ± 12.4 | 48.4 ± 8.9 | 45.3 ± 9.6 | 49.2 ± 12.0 | 48.9 ± 12.6 | 50.9 ± 9.0 |

* = significantly different from BF condition ($p < 0.05$)
AL, AM = Direction of perturbation mechanism, anterolateral and anteromedial, respectively.
BF = barefoot, R0, R1, R2 = ski binding ramp angles of 0°, 1°, and 2°, respectively.