JOINT COORDINATION ADAPTATIONS TO AN IMPLEMENTED RAMP ANGLE IN RECREATIONAL ALPINE SKIERS

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Most ski boot-binding complexes have a positive ramp angle. This angle is not regulated or reported in the alpine ski industry, but may influence skier balance and pressure control. Therefore joint coordination during a dynamic ski squat task with increasing boot ramp angle (0°, 1°, 2°) in alpine skiers (n=19) was investigated. Average joint coupling angles were significantly different between barefoot and ski conditions, as well as between the three ramp angles during the upward phase of a squat. The percentage of squat with uncoordinated knee-ankle joint movements tended to increase in ski conditions versus barefoot conditions, and coordinated hip-knee movement was reduced with alpine boot-binding-ski complexes. These differences in joint coordination and average coupling angles may impact skier balance and pressure control across the ski while skiing.

KEYWORDS: balance, coordination, bindings, squat, joint coupling

INTRODUCTION: The recreational alpine ski industry does not report or regulate the ramp angle elicited by the boot-binding complex, although it is considered sport-essential equipment. Some popular binding models from the 2011-2012 season increased heel heights in relation to the toe, creating a positive ramp angle (Korich, 2016). Reported binding models ranged from a modest 0.66 mm difference (Marker Baron) to a large heel-toe discrepancy of 10 mm (Rossignol SAS-110) (Korich, 2016). Depending on the mounted length of the binding, a heel piece elevated by 10 mm could equate to a ramp angle (RA) of greater than two degrees. The patentees of a binding model that increases the RA suggest that this positive angle will increase ankle flexion and thus the athletic posture of a skier (DeRocco & Higgins, 1999). Interestingly, a binding with a positive RA resulted in both slower run times and a greater pressure loading of the forefoot as compared to controls during giant slalom ski turns (Kröll, Birklbauer, Stricker, & Müller, 2006). However, currently, it is unknown whether joint coordination adaptations might occur from modifying the angle of the binding plate.

Although the biomechanical effects of RA have not been adequately researched in ski tasks, similar dual leg tasks may provide insight into their consequences. Postural adaptations resulting in a compensatory backward lean have been evidenced in studies with similarly imposed ramp angles in ice skates and angled ground surfaces (Fortin, Harrington, & Langenbeck, 1997; Lee, Lee, & Park, 2015). Additionally, weight lifting shoes with positive RAs increased knee range of motion and compensatory torso angular kinematics during more dynamic squats tasks (Legg, Glaister, Cleather, & Goodwin, 2017; Sato, Fortenbaugh, & Hydock, 2012). The dynamic nature of a squat is comparable to movements during skiing, however, it is unclear whether the restricted, sheath-like nature of a ski boot will result in similar postural and joint coordinative capabilities.

Importantly, postural changes may affect a skier's ability to control the translation of the ski by eliciting joint-specific balance and pressure modifications. Changes in joint coordination after fatiguing lifting tasks were found in conjunction with increased anterior-posterior centre of mass (CoM) excursion (Sparto, Parnianpour, Reinsel, & Simon, 1997). During dynamic skiing, changes in CoM maintenance over the base of support may have consequences to the skier's stability and ability to respond to perturbations throughout turns (Professional Ski Instructors of America, 2014). Thus, the purpose of this study was to investigate the effects of a neutral, one degree, and two degree binding ramp angle on joint coordination during ski simulated squats in recreational alpine skiers.

METHODS: Participants (male = 11, female = 8; 27 ± 5 yrs, 1.76 ± 0.11 m) were recruited from the general Marquette, MI, USA (n = 9) and Salzburg, Austria (n=10) populations. Participants were excluded from the study if they were not within 20-39 years of age or if they identified as either a "Beginner" or an "Expert" level skier. Additionally, participants presenting with lower limb deformation, injuries, or reconstruction surgeries within a year were excluded from the study. Permission for this study was obtained from the university's Institutional Review Board (HS 17-868).

Three dimensional (3D) motion (sampling frequency = 250 Hz) was captured during four squat conditions: barefoot (BF; consequently a 0° ramp angle), ski booted with posterior to anterior ramp angle of 0° (R0), 1° (R1) and 2° (R2). These angles were accomplished by the adjustable see-saw mechanism of the SensoWip binding (Kröll, Birklbauer, Stricker, & Müller, 2006). In each condition, ten dynamic squats were executed at a metronome controlled rhythm of 36 bpm that simulated the tempo of skiing (Seifert, Kröll, & Müller, 2009). The barefoot condition was performed first, followed by R0, R1, and R2 in a randomized counterbalanced order. In the ski conditions, stance width was controlled based on the measured hip width of each participant and ski contact area was standardized to a length of 0.12 m. All participants used the same model of ski.

Motion capture was recorded with 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. A cluster based marker set with anatomical reference frames was used and raw kinematic data were filtered with a 9-Hz Butterworth filter (Hewett et al., 2005; Selbie, Hamill, & Kepple, 2013). Visual 3D x64 Professional (v6.01.18; Germantown, MD USA) was used to calculate the sagittal plane joint angles of the ankle, knee, and hip during each squat condition. Knee-to-ankle and hip-to-knee coupling was then assessed separately via vector coding, during the downward (DP) and upward phases (UP) of the squat (Needham, Naemi, & Chockalingam, 2014). These phases were defined by the "transition points" where the pelvis segment assumed a velocity of zero. Within these phases, the coordinated relationship of the two joints being coupled was assessed by a percentage of the cycle spent in each coordinative pattern: when the movement was primarily driven by the proximal joint, distal joint, or with the two joints in-phase, or anti-phase. SPSS Statistics v.24 was used to assess within subjects repeated measures ANOVAs ($\alpha = 0.05$) for condition (BF, R0, R1, R2) during the DP, UP, and coordination couples independently. Additionally, significant differences in coordination were investigated in relation to leg dominance. A group average coupling angle (CA) throughout squat phase was created for each joint pair (DP + knee-ankle; UP + knee-ankle; DP + hip-knee; UP + hip-knee). Group mean differences across condition were then analysed via a nonparametric Friedman test, as significant skewness and kurtosis were detected. Significance was subsequently assessed by a Wilcoxon Signed Ranks test and evaluated to an adjusted alpha for six comparisons ($\alpha = 0.0083$).

RESULTS & DISCUSSION: Mean CA was significantly different between all conditions (BF > R0, R1, & R2; R0 > R1 > R2) for the UP of both the knee-ankle and hip-knee coupling ($p < 0.0083$; Figure 1). 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. 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. Importantly, these differences in the average CA indicate significant ramp elicited changes in the joint relationships during the squat phases, with the exception of the hip-knee pair in the DP of the squat.

No significant differences were found between the dominant and non-dominant legs. When knee-ankle coupling 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 1). Ski task in-phase knee-ankle coordination increased compared to BF through the entire squat, with the exception of R2 in the squat UP (Table 1). Because of the joint model used, this indicates that these two joints were spending more time performing uncoordinated coupled movements (i.e. extension and flexion). Interestingly, this effect had a tendency toward a lesser in-phase contribution with increasing ramp. 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). Otherwise, no additional effects were seen between ramp interventions R0-R2 during any other coordination phases.

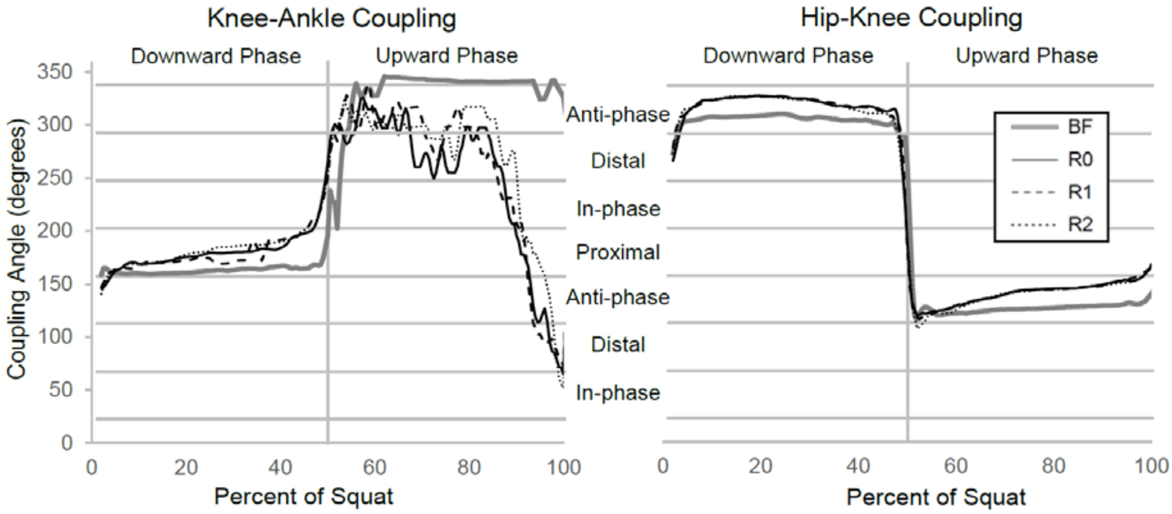

Figure 1. Average coupling angles of knee-ankle and hip-knee coordination during one squat are displayed for the non-dominant leg. The coupling pattern (movement driven by the distal joint, proximal joint, or in-phase/anti-phase joint contribution) is labelled for each angle range for which it is associated.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

Table 1. Knee to ankle coordination is displayed by coupling pattern and expressed as a percentage of the downward and upward phases of a squat task in four conditions: barefoot (BF), and ski binding ramp angles of 0° (R0), 1° (R1), and 2° (R2). Coupling pattern = knee, ankle, in-phase, and anti-phase. Significant differences (p<0.05) compared to BF (*) and R0

	Knee-Ankle Coupling							
	Down Phase				Up Phase			
	BF	R0	R1	R2	BF	R0	R1	R2
Knee	82.5 ± 3.7	83.6 ± 1.6	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

The greatest percentage of squat was spent in anti-phase hip-knee coordination during both DP and UP (88.2 - 94.6%; Table 2). This indicates these two joints were coordinated in flexion (DP) or extension (UP). 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 2). 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. Lesser in-phase contribution with R2 in the squat DP of both coordination couples indicate that the increased percentage of time spent in the uncoordinated angular movement cannot explain the increased run time measured with a positive RA by Kröll et al. (2006). However, changes in movement coordination may have further consequences on the translation and pressure distribution of the ski on the snow (Professional Ski Instructors of America, 2014).

Small, but significant increases seen in both the ankle-knee and hip-knee uncoordinated joint movements seen with ski tasks may effect a skier's postural control and balance during dynamic skiing. For example, statically, excessive ankle flexion coupled with knee extension tends to anteriorly shift the CoM, which would subsequently shift the location of the centre of

Table 2. Hip to knee coordination is displayed by coupling pattern and expressed as a percentage of the downward and upward phases of a squat task in four conditions: barefoot (BF), and ski binding ramp angles of 0° (R0), 1° (R1), and 2° (R2). Coupling pattern = hip, knee, in-phase, and anti-phase. Significant differences (p<0.05) compared to BF (*)

	Hip - Knee Coupling							
	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*

pressure anterior (Professional Ski Instructors of America, 2014). Thus, the increased forefoot loading measured by Kröll et al. (2006) may occur due to changes in joint coordination patterns such as those reported in this study. Further, 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). This suggests that similar changes in joint contributions as seen in coordination couples may also be associated with decreased postural stability and thus increased risk of balance loss during skiing.

CONCLUSIONS: The addition of an alpine boot-binding-ski complex alters the joint coupling of recreational alpine skiers during ski-simulated squats. Additionally, the ramp angle of the binding affected the average knee-ankle and hip-knee joint coupling angles in the upward phase of a squat. Ramp angle also affected the downward phase of the knee-ankle joint coordination. The joint coupling angle changes may be consequential to fall risk during dynamic alpine skiing because it may alter the relationship of the centre of mass to the base of support. Further investigation into balance via centre of pressure excursion may provide insight to fall risk associated with these changes.

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