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Complete List of Authors:	Jordan, Matthew; Human Performance Laboratory, University of Calgary; Matt Jordan, Matt Jordan Aagaard, Per; University of Southern Denmark, Department of Sports Science and Clinical Biomechanics Herzog, Walter; University of Calgary, Human Performance Laboratory
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Lower Limb Asymmetry in Mechanical Muscle Function: A Comparison Between Ski Racers With and Without ACL Reconstruction

Authors: Matthew J. Jordan[1]
Per Aagaard[2]
Walter Herzog[1]

Affiliation: [1] Human Performance Laboratory
The University of Calgary
2500 University Drive NW
Calgary, Alberta
T2N 1N4
[2] Department of Sports Science and Clinical Biomechanics,
University of Southern Denmark
Campusvej 55, DK-5230 Odense M, Denmark

Correspondence: Matthew J. Jordan
Canadian Sport Institute-Calgary
2500 University Drive NW
Calgary, Alberta
T2N 1N4
Email: mjordan@ucalgary.ca
Phone: (403) 714-4655

ABSTRACT

Due to a high incidence of anterior cruciate ligament (ACL) re-injury in alpine ski racers, the aim was to assess functional asymmetry in the countermovement jump (CMJ), squat jump (SJ) and leg muscle mass in elite ski racers with and without anterior cruciate ligament reconstruction (ACL-R). Elite alpine skiers with ACL-R (n=9; 26.2±11.8 months post-op) and uninjured skiers (n=9) participated in neuromuscular screening. Vertical ground reaction force during the CMJ and SJ was assessed using dual force plate methodology to obtain phase-specific bilateral asymmetry indices (AI) for kinetic impulse (CMJ and SJ phase-specific kinetic impulse AI). Dual X-Ray absorptiometry (DXA) scanning was used to assess asymmetry in lower body muscle mass. Compared to controls, ACL-R skiers had increased AI in muscle mass ($P<0.001$), kinetic impulse AI in the CMJ concentric phase ($P<0.05$) and the final phase of the SJ ($P<0.05$). Positive associations were observed between muscle mass and AI in the CMJ concentric phase ($r=0.57$, $P<0.01$) as well as in the late SJ phase ($r=0.66$, $P<0.01$). Future research is required to assess the role of the CMJ and SJ phase-specific kinetic impulse asymmetry index as a part of a multi-faceted approach for improving outcome following ACL-R in elite ski racers.

KEYWORDS: knee injury; vertical jump; injury prevention; return to sport screening

INTRODUCTION

Elite alpine ski racing (i.e. FIS World Cup, World Championship, Olympic level racing) occurs at high speeds and in an unpredictable environment with repeated bi-directional turning composed of forceful concentric but predominantly eccentric movements that elicit near maximal levels of lower body muscle activation (Hintermeister et al., 1995; Berg et al., 1995; Bere et al., 2011). To contend with these physical demands, competitive alpine ski racers are characterized by having a high degree of bilateral thigh muscle strength symmetry (Neumayr et al., 2003) along with a high degree of force symmetry in multi-joint closed kinetic chain movements (Patterson et al., 2009).

Due to the intense nature of alpine ski racing, there is a high risk for lower body injury especially to the knee joint (Flørenes et al., 2009; Bere et al., 2014). Knee injuries account for nearly one third of the injuries sustained by elite ski racers and half of these injuries result in a significant time lost from sport (> 28 days) (Flørenes et al., 2009; Bere et al., 2014). Anterior cruciate ligament (ACL) injury is the most common type of knee injury (Flørenes et al., 2009; Bere et al., 2014) and ski racers are at high risk for ACL re-injury (Stevenson et al., 1998; Pujol et al., 2007). ACL injury in elite alpine ski racing is distinct from field sports due to the existence of three distinct injury mechanisms that occur in a highly unpredictable and changing environment (Bere et al., 2011). Additionally, recently conducted studies indicate there are no sex-related differences in ACL injury rates in elite ski racers, which has been attributed to the exclusion of sex-related factors as a result of the high force injury mechanisms (Flørenes et al., 2009; Bere et al., 2014).

Despite the high ACL injury rates and the uniqueness of non-contact ACL injuries in ski racing, only a single longitudinal study has focused on identifying modifiable (trainable) risk factors for ACL injury (Raschner et al., 2012). Furthermore, in consideration of the high ACL re-injury rate (Stevenson et al., 1998; Pujol et al., 2007), very little is known about the neuromuscular function of elite ski racers with a history of ACL injury and ACL reconstruction (ACL-R), and there are no scientifically supported standards or criteria guiding the return to sport period following ACL injury. This is important as following an ACL-R the primary objectives are to restore neuromuscular function with rehabilitation exercise (Palmieri-Smith et al., 2008), ensure athlete safety for return to sport and re-establish pre-injury performance levels (Myer et al., 2006). However, known risk factors for ACL injury, such as deficits in thigh muscle strength and increased bilateral limb asymmetry during multi-joint lower body movements often persist in non-athlete populations following ACL injury and ACL-R despite rehabilitation and return to normal activities (Berchuk et al., 1990; Noyes et al., 1991; Salem et al., 2003; Tsepis et al., 2006; Paterno et al., 2007; Castanharo et al., 2011; Krishan & Williams, 2011; Holsgaard-Larsen et al., 2013).

Following ACL-R, the rehabilitative process is divided into the early-phase and late-phase of rehabilitation with the latter phase including the transition to return to sport (Myer et al., 2006). At the return to sport phase, objective and sport-specific neuromuscular screening including functional testing is important to ensure athlete readiness and safety, and that pre-injury functional ability is restored (Myer et al., 2006). Evaluating subjects even up to two years post ACL-R is important due to the potential for prolonged deficits in function (Ernst et al., 2000; Paterno et al., 2007; Castanharo et al., 2011). Due to the high ACL re-injury rates in elite ski racing and the large physical demands, return to sport (i.e. return to snow) screening is important for ski racers following ACL-R. Neuromuscular testing and functional tests should also be easily administered within a high performance sport environment. In this context, assessing bilateral limb asymmetry in multi-joint movements has been proposed as an effective approach to objectively differentiate between normal and pathological movement behaviors (Herzog et al., 1989; Holsgaard-Larsen et al., 2013), and to assess progress in rehabilitation (Herzog et al., 1989; Impellizzeri et al., 2007). Functional asymmetry testing has also been used to differentiate between ACL deficient individuals who return to high level physical activity versus those who do not (Fitzgerald et al., 2000), and within a framework of return to sport functional screening for ACL-R athletes (Myer et al., 2006).

In order to assess ACL-R skiers, it is important that functional neuromuscular testing be multi-faceted and reflects the demands of ski racing, which includes repeated bilateral eccentric/concentric movements (Hintermeister et al., 1995; Berg et al., 1995). In addition, such tests should reflect deficits that are commonly found in ACL-R subjects including reduced hamstrings and quadriceps strength/power (Hiemstra et al., 2000). By assessing lower-limb asymmetry over specific phases of the vertical jump (phase-specific) using a dual force plate system, knee extensor power and the ability to perform eccentric/concentric movements can be assessed (Caserotti et al., 2001; Thorlund et al., 2008; Jakobsen et al., 2012). Through analysis of the vertical ground reaction force in the countermovement jump (CMJ) the eccentric and concentric movement phases can be identified and functional asymmetry can be calculated over these distinct phases (Caserotti et al., 2001; Thorlund et al., 2008; Jakobsen et al., 2012). Furthermore, as jumping involves a proximal to distal sequence of joint torques deficits in knee extensor power can be identified by examining the vertical ground reaction force in the mid to late phase of the squat jump (SJ) where the knee extensors are involved to a larger extent (Bobbert & van Soest, 2001). Using this phase-specific approach the magnitude of the vertical ground reaction force can be obtained by calculating the kinetic impulse or the area under the force-time curve (CMJ and SJ phase-specific kinetic impulse), which permits characterization of the functional asymmetry over a greater portion of the force-time curve than discreet time point analysis with values such as the instant of peak vertical ground reaction force.

The purpose of this study was to quantify bilateral lower limb functional asymmetry using the CMJ and SJ phase-specific kinetic impulse asymmetry index in uninjured and ACL-R elite ski racers and asymmetry in lower limb muscle mass measured with dual x-ray absorptiometry scanning (DXA). We hypothesized that ACL-R ski racers would display significantly greater CMJ and SJ phase-specific kinetic impulse asymmetry indices compared to uninjured ski racers (Paterno et al., 2007; Castanharo et al., 2011). It was also expected that ACL-R ski racers would demonstrate greater asymmetry in leg muscle mass, which may be associated with the degree of functional asymmetry measured during the CMJs and SJs

MATERIAL & METHODS

Subjects

Eighteen actively competing elite alpine ski racers from the Canadian Alpine Ski Team including five World Cup medalists were recruited during an annual fitness testing session at the start of the off-snow training period. Due to the challenges for subject recruitment in an elite athlete population, only nine actively competing elite ski racers suffering primary ACL injury/ACL-R (Males: n=4; Females: n=5), and nine uninjured ski racers (Males: n=5, Females: n=4) could be recruited, and a comparison between sexes was not made. The pattern of secondary injury associated with the primary ACL injury was consistent with reports from alpine skiing populations and included meniscus injury, medial collateral ligament injury and articular cartilage injury (Paletta et al., 1992; Granan & Inacio, 2013). Subject characteristics (Mean±SD) are provided in Table 1. All subjects had medical clearance for ski training and racing. Individuals who were being treated for lumbar spine injury and/or unrelated lower limb injury such as patellofemoral knee pain and recent leg fractures were excluded from the study. Ski racers with primary ACL injury who also sustained secondary injury to other knee ligaments, articular cartilage injury and meniscus injury were included in this study. Inclusion criteria for both subject groups included that the subjects were qualified for and competed in FIS World Cup competition for the subsequent competitive season following testing. The Conjoint Faculties Research Ethics Board at the University of Calgary approved the experimental protocol and all subjects gave written informed consent to participate in this study.

Test Procedures

The functional asymmetry assessment was undertaken as a part of routine annual pre-season testing at the start of the off-snow training period. However, DXA scanning and the CMJ and SJ phase-specific kinetic impulse asymmetry index were newly introduced tests, therefore, we were unable to obtain pre-injury data. All subjects were highly familiar with the testing procedures, and regularly performed maximal effort CMJs and SJs as a part of their off-snow training routines. After giving informed consent, body composition was assessed by dual energy X-Ray absorptiometry (DXA) scanning. Following DXA scanning, subjects performed a standardized warm-up including ten minutes on a cycle ergometer and light dynamic stretching for the lower body. Dynamic stretching targeted the muscles of the lower limbs (i.e. quadriceps, hamstrings, gluteal muscles, hip flexors and plantar flexors) and included ten repetitions of dynamic stretching with a two-second hold in the stretched position.

Subjects then performed ten maximal CMJs where they were instructed to descend rapidly to a knee joint angle of 90 degrees knee flexion and ascend maximally while keeping the hands firmly placed on the hips. Subjects were given a five-minute rest interval, which was followed by ten maximal SJs. For the SJs, subjects were instructed to descend slowly to a knee joint angle of 90 degrees knee flexion and remain stationary for three-seconds. After achieving a stationary baseline force, subjects were given verbal instruction to jump. Subjects were instructed to jump maximally on each jump and as with the CMJs, subjects were required to keep the hands firmly placed on the hips throughout the jump. For both the CMJ and SJ trials, jumps that deviated from the required technique were discarded and then repeated. All jump variables were calculated as the mean value obtained from ten jumps.

Force Plate Analysis

Subjects performed the CMJs and SJs on a dual force plate system (Pasco, Model No: PS 2142) that was capable of simultaneously measuring the vertical ground reaction force (Fz) recorded at 500 Hz sampling frequency during the jumps. Data were recorded on a personal computer and then exported and analyzed using a custom-built computer program (Matlab R 2012a) according to procedures described elsewhere (Caserotti et al., 2001; Thorlund et al., 2008; Jakobsen et al., 2012). Briefly, the velocity of the body centre of mass (BCM) was obtained by time integration of the instantaneous acceleration signal calculated from Fz. From the velocity of the BCM, the eccentric deceleration phase was defined as the time interval from the maximum negative velocity to zero velocity (deepest BCM position), whereas the concentric phase was defined from this instant of zero BCM velocity to the instant of jump takeoff (Figure 1). The total kinetic impulses for the right and left limb were then calculated separately for the eccentric deceleration phase and concentric phase by time integration of the force-time curve over the appropriate periods.

The SJ was divided into two separate phases (Figure 1). Phase 1 was defined as the initiation of the jump (i.e. Time = 0) to the mid-point of the jump (i.e. Time = ½ of the total jump time). Phase 2 was defined as the time interval from the mid-point of the jump (i.e. Time = ½ of the total jump time) to takeoff. As with the CMJ, integration of the force-time curve over the appropriate time periods provided the kinetic impulse for the right and left limb. The use of a phase-specific kinetic impulse calculation was undertaken based on pilot data observations of the force-time tracings of ACL-R skiers that revealed directional asymmetries throughout SJs and CMJs thus providing a rationale for the proposed approach. A typical example is provided in Figure 2.

For both the SJ and the CMJ, instantaneous mechanical muscle power was obtained by multiplying instantaneous vertical ground reaction force (Fz) with the corresponding BCM velocity. Peak power was defined as the maximum power in the concentric jump phase and was normalized relative to body mass.

Body Composition

Thigh lean mass and body fat percentage were determined by DXA scans according to the manufacturer's instructions (Discovery A QDR, Software version 12.6.2, Hologic Inc., Waltham, MA, USA). The same technician performed the analysis for all the DXA scans.

Asymmetry Index Calculation

The CMJ and SJ phase-specific kinetic impulse asymmetry index was calculated in order to maintain the directionality of the asymmetry (Impellizzeri et al., 2007). For the control group, the asymmetry index was calculated as:

$$\text{Asymmetry Index} = \frac{\text{(Left Limb Impulse–Right Limb Impulse)}}{\text{(Maximum of Left and Right Impulse)}} * 100,$$

where a positive number indicated a left leg dominance and a negative number a right leg dominance.

For the ACL-R ski racers, the asymmetry index was calculated as:

$$\text{Asymmetry Index} = \frac{\text{(Uninjured Limb Impulse – ACL-R Limb Impulse)}}{\text{(Maximum of Left and Right Impulse)}} * 100,$$

such that a positive number indicated uninjured limb dominance and a negative number indicated dominance in the ACL-R limb.

Statistical Analysis

Based on pilot data, a statistical power calculation was performed and a minimum sample size of eight subjects per group was deemed necessary to achieve a statistical power of 80% (β=0.80) in the primary outcome variables. We expected to find a 10% difference in the kinetic impulse asymmetry index between ACL-R ski racers and uninjured ski racers. Where appropriate a one-way analysis of variance was used to compare the means between the control group and the ACL-R group. Due to unequal variances, a one-way test with unequal variances (oneway.test in Stats Package, R) was used to compare the asymmetry index for the concentric phase of the CMJ, the eccentric deceleration phase of the CMJ, Phase 1 of the SJ and Phase 2 of the SJ. Subsequently, a linear regression analysis was performed to assess the relationship between the asymmetry index in leg muscle mass and the asymmetry index CMJ and SJ phase-specific kinetic impulse asymmetry index. Statistical analysis was carried out using R (Version 0.97.551). All data is reported as the mean value ± one standard deviation (SD) unless otherwise stated. A statistical significance level of α = 0.05 was chosen.

RESULTS

ACL-R ski racers showed greater asymmetry indices compared to uninjured ski racers in the concentric phase of the CMJ ($P<0.05$), Phase 2 of the SJ ($P<0.05$), and in leg muscle mass [$F(1, 16) = 22.3$; $P<0.001$] (Table 2). Data for the CMJ and SJ phase-specific kinetic impulse for the right and left limb are presented in Table 3. There were no statistically significant differences observed between groups for Phase 1 of the SJ ($P=0.32$) and the eccentric deceleration phase of the CMJ (P=0.32). Linear regression analysis examining the relationship between the CMJ and SJ kinetic impulse asymmetry index and asymmetry index in leg muscle mass for all ski racers revealed a moderate relationship for the concentric phase of the CMJ [$r = 0.57$; $F(1, 16) = 8.7$, $P < 0.01$) and Phase 2 of the SJ [$r = 0.66$; $F(1,16) = 13.64$, $P < 0.01$] (Figure 3). Additionally, large inter-individual variation was observed in the directionality of the CMJ phase-specific kinetic impulse asymmetry index for the ACL-R skiers in the eccentric deceleration phase of the CMJ.

DISCUSSION

To the authors' best knowledge, the present study is the first to evaluate bilateral asymmetry in leg muscle mass and functional asymmetry during multi-joint closed kinetic chain movements in actively competing ACL-R elite ski racers and uninjured ski racers including World Cup medalists. Such investigations are important due to the high incidence of ACL injury and re-injury in this athlete population (Stevenson et al., 1998; Pujol et al., 2007; Flørenes et al., 2009; Bere et al., 2014). Furthermore, neuromuscular testing and functional asymmetry assessments are useful throughout the return to sport process to ensure neuromuscular function is adequately restored and to help guide the post ACL-R rehabilitation process (Myer et al., 2006).

The present investigation offers an applicable assessment of functional asymmetry evaluating kinetic impulse over specific phases of the CMJ and SJ (phase-specific kinetic impulse asymmetry index). The CMJ and SJ phase-specific kinetic impulse asymmetry index addresses the limitations of using single discrete time point analysis with values such as the instant of maximum ground reaction force (Nigg et al., 2013). By evaluating the magnitude of the ground reaction force using kinetic impulse calculations (i.e. area under the force vs. time curve) it is possible to obtain information on functional between-limb asymmetry over a broader selection of the jump force-time curve using a straightforward mathematical approach.

As ski racing involves repeated bidirectional turning with eccentric/concentric movements and large quadriceps muscle loading (Hintermeister et al., 1995; Berg et al., 1995), the ability to identify deficits specific to eccentric and concentric muscular actions from CMJ force-time analysis may provide additional diagnostic information for rehabilitation due to the distinct nature of eccentric versus concentric muscular actions (Aagaard et al., 2003). Additionally, ACL injury and ACL-R result in chronic knee extensor strength and power deficits (Hiemstra et al., 2000; Palmieri-Smith et al., 2008). Assessing functional asymmetry in the mid to late phase of the SJ using jumping kinetics enables the quadriceps muscle group to be evaluated due to the greater contribution of the knee extensors in the proximal to distal sequence of the SJ movement (Bobbert & van Soest, 2001; Dai et al., 2013). However, it should be mentioned that muscular deficits following ACL-R are not limited to the knee extensors (Hiemstra et al., 2000), and a comprehensive approach for return to sport screening and neuromuscular testing is recommended (Myer et al., 2006).

The main finding of our study was the presence of a significantly greater CMJ and SJ phase-specific kinetic impulse asymmetry index in top-level ski racers with a history of ACL-R compared to uninjured ability-matched ski racers that remained despite a full return to activity. The finding of elevated functional asymmetry conforms to findings in non-athletic populations where ACL deficient and ACL-R subjects exhibit elevated bilateral asymmetry during multi-joint lower body movements such as jumping and squatting (Ernst et al., 2000; Salem et al., 2003; Paterno et al., 2007; Castanharo et al., 2011; Holsgaard-Larsen et al., 2013) even up to two-years post-surgery (Paterno et al., 2007; Castanharo et al., 2011).

However, the CMJ and SJ phase-specific kinetic impulse asymmetry index used in the present investigation revealed individuals with directional shifts in the limb asymmetry throughout the jumping movement, and distinct jump-phases in which the asymmetry index was the most prominent for the ACL-R subjects. Specifically, differences in limb asymmetry between ACL-R and uninjured skiers were observed for the concentric phase of the CMJ and the mid to late phase of the SJ (i.e. Time = ½ of the total flight time to takeoff) but not for the eccentric deceleration phase of the CMJ or the first phase of the SJ (i.e. Time = 0 to ½ of total jump time). This result may be a reflection of the chronic knee extensor strength and power deficits associated with ACL injury (Hiemstra et al., 2000; Palmieri-Smith et al., 2008), and the importance of the quadriceps muscle group for maximal mechanical muscle power generation in the proximal to distal sequence of joint actions in the jumping movement (Bobbert & van Soest, 2001).

While a statistically significant difference was not found in the eccentric deceleration phase, careful review of each individual subject revealed a single subject who displayed a large eccentric deceleration asymmetry (Asymmetry Index of -16.1%) that reflected dominance in the ACL-R limb. This finding was unexpected and emphasizes the importance of maintaining the directionality of the asymmetry index. Furthermore, for practical purposes it also emphasizes the need to account for the presence of inter-subject variation in the CMJ phase-specific kinetic impulse asymmetry index.

Consistent with the limited scientific data on lower body functional asymmetry in alpine ski racers (Patterson et al., 2009), the present group of uninjured elite alpine ski racers was highly symmetric across all phases of the SJ and CMJ (Range = 0.5% to 2.2%). Our results are consistent with other findings of marked bilateral limb symmetry in elite ski racers including a quadriceps maximal strength asymmetry of less than 2% in male and female elite alpine ski racers (Neumayr et al., 2003). The precise relationship between a low functional asymmetry index, ski performance and risk for injury is unknown. However, due to the bidirectional nature of ski racing and the large quadriceps muscle loading (Hintermeister et al., 1995; Berg et al., 1995), elevated functional asymmetry would seem disadvantageous. Additionally, a prospective cohort study of over 400 young competitive alpine ski racers found that a significant proportion of first time lower extremity injuries occurred on the left limb compared to the right limb (Westin et al., 2012). As there were no physical or functional testing measurements conducted in this study, the mechanisms underlying this finding are unknown. However, these findings provide a rationale for including functional asymmetry profiling using tests such as the CMJ and SJ phase-specific kinetic impulse asymmetry index in competitive alpine ski racers. Future longitudinal study is required to confirm the possibility of a relationship between increased bilateral functional asymmetry and risk for lower extremity injury.

Representing a single case observation, an ACL-R athlete experienced an MCL injury to the contralateral limb in the period following the data collection that was sustained during ski training. ACL re-injury is common in elite ski racers (Stevenson et al., 1998; Pujol et al., 2007), and injury is often sustained on the contralateral limb (Pujol et al., 2007). While this subject did not sustain a re-injury to the ACL, this occurrence has relevance to the phase-specific kinetic impulse asymmetry index as this athlete had the greatest asymmetry in the mid to late phase of the SJ (Asymmetry Index of 25.3%), the CMJ concentric phase (Asymmetry Index of 18.0%) and the CMJ eccentric deceleration phase (Asymmetry Index of 20.5%).

In other return to sport screening frameworks ensuring a between limb asymmetry of less than 15% has been recommended for functional tests involving jumping movements (Myer et al., 2006). Additionally, in athlete and non-athlete populations, functional deficits in multi-joint closed kinetic chain movements are associated with risk for ACL injury and outcome following

ACL-R (Noyes et al., 1991; Hewett et al., 2005; Donelly et al., 2012; Taylor et al., 2013). Despite the potential relevance for including the CMJ and SJ phase-specific kinetic impulse asymmetry index as a part of a multi-faceted approach for assessing outcome in the ACL-R ski racer, well-conducted longitudinal studies are lacking. Therefore, at the present time it is impossible to confirm or disprove the value of this approach for identifying skiers who may be at elevated risk for injury following ACL-R.

Consistent with the literature, ACL-R ski racers also had significantly greater bilateral asymmetry in leg muscle mass compared to uninjured ski racers reflecting deficits in the affected limb (Tsepis et al., 2006; Konishi et al., 2012; Krishan & Williams, 2011). However, while Konishi and colleagues (2012) found significant deficits in muscle volume in ACL-R patients less than 12 months post-surgery, no statistical difference was observed at 18 months post-surgery. In the present investigation, time since surgery was 23.5±10.6 months for the male and 28.4±13.5 months for the female skiers, which is longer than the 18 month post-operative period evaluated by Konishi et al. (2012). The reason for the difference in findings between the two studies is unclear but may be attributable to the different populations studied (elite athlete vs. untrained) and/or due to the prolonged asymmetrical limb loading as a consequence of the extreme physical demands of elite alpine ski racing. There is also evidence highlighting the importance of rehabilitation to restore thigh muscle strength in ACL deficient subjects (Tsepis et al., 2006). In the present investigation, we were unable to obtain specific information regarding each subject's rehabilitation program. However, all subjects received supervised and individualized rehabilitation provided by physiotherapists assigned to the Canadian Alpine Ski Team.

Finally, a moderate relationship was found between the asymmetry index in leg muscle mass and kinetic impulse in the concentric phase of the CMJ ($r = 0.57$). This was further supported with a moderately strong relationship observed between the asymmetry index in leg muscle mass and the kinetic impulse asymmetry index for Phase 2 of the SJ ($r = 0.66$). In addition to muscle mass, neuromuscular coordination is highly important for performance in movements requiring large impulses and fast rates of force development such as the CMJ and SJ (Aagaard, 2003). While impaired central activation has not been observed in active ACL-R subjects, deficits in neuromuscular coordination and/or activation in ACL-R ski racers cannot be excluded (Krishan & Williams, 2011).

A limitation of our study was the inability to control for sex-related factors. However, previous research suggests that there is no difference in ACL injury rates between male and female elite ski racers due to the preclusion of sex-related risk factors commonly found to be dominant in field sports due to the high energy injury mechanisms (Flørenes et al., 2009; Bere et al., 2014). Further limitations include a seven-year age difference between the ACL-R males and uninjured males, and a relatively small sample size. Despite these limitations and the inherent challenges in studying elite athlete populations it is important that research efforts be specific to the population of interest in order to develop effective injury prevention strategies (Van Mechelen et al., 1992). As the CMJ and SJ phase-specific kinetic impulse asymmetry index and DXA scanning were only recently introduced into the annual pre-season fitness assessments, we do not have pre-injury measurements. Such information would be valuable in order to determine if the increased functional asymmetry was present prior to the ACL injury, and if not the degree to which functional asymmetry was affected following ACL-R. Obtaining this type of baseline functional data on uninjured ski racers is an important outcome for future studies.

In conclusion, using dual force plate methodology to assess functional asymmetry it was observed that actively competing elite alpine ski racers with a history of ACL-R displayed an elevated CMJ and SJ kinetic impulse asymmetry index over specific phases of the jumping movement including the concentric phase of the CMJ and in the mid to late phase of the SJ compared to uninjured ski racers. For both of these jump phases, the kinetic impulse asymmetry index reflected deficits in the affected limb. In addition, ACL-R ski racers also displayed greater asymmetry in leg muscle mass compared to uninjured ski racers who were highly symmetrical across all outcome measures. Due to the moderate relationship between the CMJ and SJ phase-specific kinetic impulse asymmetry index and the asymmetry index in leg muscle mass, future research should include measures of neuromuscular activation (including antagonist muscle co-activation) and muscle synergist coordination as potential mechanisms contributing to the functional asymmetries observed in ACL-R ski racers. Further longitudinal research is required to assess the value of the CMJ and SJ phase-specific kinetic impulse asymmetry index as a part of a multi-faceted approach for return to sport screening and monitoring to ensure pre-injury performance levels are restored, and to evaluate the relationship between elevated functional asymmetry and risk for re-injury.

PERSPECTIVES

Elite ski racing is an extreme sport with a high incidence of knee injury and re-injury. Due to the large physical demands, objectively obtained functional criteria are important to monitor progress in rehabilitation following ACL-R and to establish objective standards for a safe return to sport. The present investigation introduces a new approach to evaluate functional asymmetry using the CMJ and SJ phase-specific kinetic impulse asymmetry index. By measuring the limb kinetic impulse over specific phases of the CMJ and SJ, this approach provides information relevant to functional movements involved in ski racing (e.g.

eccentric/concentric movements), yet, is a straightforward analytical technique that offers more information than discrete time point analysis. This investigation reveals the presence of significant functional asymmetry during specific phases of the CMJ and SJ in elite ski racers with a history of ACL-R compared to uninjured ski racers despite a full return to sport. Further research using prospective study designs are required to evaluate the use of this functional asymmetry assessment as a part of a multi-faceted approach for return to sport screening following ACL injury in elite ski racers.

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TABLE 1. Subject characteristics (Mean±SD)

STATUS	SEX	n	AGE (years)	MASS (kg)	BODY FAT (%)	MONTHS POST-OP	CMJ PEAK POWER (W/kg)	SJ PEAK POWER (W/kg)
ACL-R SKIERS	FEMALE	5	23.8±3.3	70.3±5.7	21.6±2.5	28.4±13.5	40.4±5.4	40.4±6.2
	MALE	4	30.5±2.1	86.6±9.9	14.7±3.1	23.5±10.6	49.9±3.9	50.1±3.3
UNINJURED SKIERS	FEMALE	4	21±1.4	66.8±4.5	15.3±2.5	NA	45.2±3.8	43.5±5.0
	MALE	5	23.4±2.5	80.7±1.7	13.8±2.2	NA	52.7±4.9	52.3±4.3

TABLE 2. Mean asymmetry index (AI) for muscle mass, countermovement jump (CMJ) and squat jump (SJ) phase-specific kinetic impulse and 95% confidence interval for uninjured skiers and ACL-R skiers (* P < 0.05; **P<0.001).

VARIABLE	STATUS	MEAN (%)	95% CONFIDENCE INTERVAL (%)
AI CMJ CONCENTRIC	ACL-R	6.8*	1.5 to 12.0
	UNINJURED	0.5	-1.3 to 2.4
AI CMJ ECCENTRIC	ACL-R	5.2	-4.5 to 14.9
	UNINJURED	1.0	-1.5 to 3.5
AI SJ PHASE 1	ACL-R	-2.6	-11.3 to 6.2
	UNINJURED	1.0	-1.9 to 4.0
AI SJ PHASE 2	ACL-R	8.8*	0.1 to 17.6
	UNINJURED	-1.0	-4.2 to 2.2
AI MUSCLE MASS	ACL-R	4.3**	1.5 to 7.0
	UNINJURED	-2.2	-3.8 to -0.6

TABLE 3. Data of countermovement jump (CMJ) and squat jump (SJ) phase-specific kinetic impulses for right and left limbs in ACL-R skiers and uninjured skiers (Mean±SD).

VARIABLE	SEX	ACL-R SKIERS		UNINJURED SKIERS	
		ACL-R LIMB	OTHER LIMB	LEFT	RIGHT
IMPULSE SJ PHASE 1 (Ns)	FEMALE	160.5±35.9	146.9±41.8	183.5±45.3	176.3±40.5
	MALE	199.6±45.2	215.0±46.8	231.3±18.0	233.5±16.6
IMPULSE SJ PHASE 2 (Ns)	FEMALE	68.3±18.8	71.5±17.4	52.5±9.6	53.1±8.8
	MALE	79.2±18.6	92.1±22.9	56.6±11.7	56.9±11.1
IMPULSE CMJ ECCENTRIC (Ns)	FEMALE	108.6±7.8	104.2±14.2	108.0±21.0	104.8±16.5
	MALE	128.0±14.2	154.5±13.1	139.7±9.3	139.9±8.5
IMPULSE CMJ CONCENTRIC (Ns)	FEMALE	169.7±16.2	173.9±20.0	174.8±27.3	171.2±24.5
	MALE	213.9±21.6	245.0±26.6	223.9±8.7	225.0±6.8
LEG MASS (g)	FEMALE	9009.2±969.0	9429.3±1254.4	9215.2±763.1	9363.2±701.2
	MALE	11519.2±1945.3	12022.8±1720.4	10981.6±548.9	11285.3±453.4

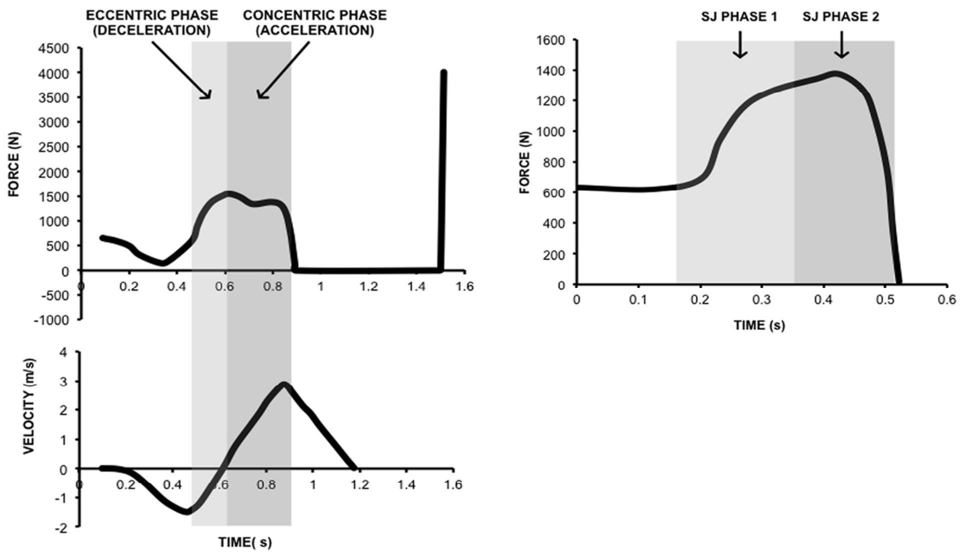

FIGURE 1. Plots on the left identify the countermovement jump (CMJ) eccentric deceleration phase and concentric phase using the velocity of the body centre of mass. Plot on the right side identifies squat jump (SJ) Phase 1 (Time = 0 to Time = ½ of total jump time) and Phase 2 (Time = ½ of total jump time to takeoff).
69x40mm (600 x 600 DPI)

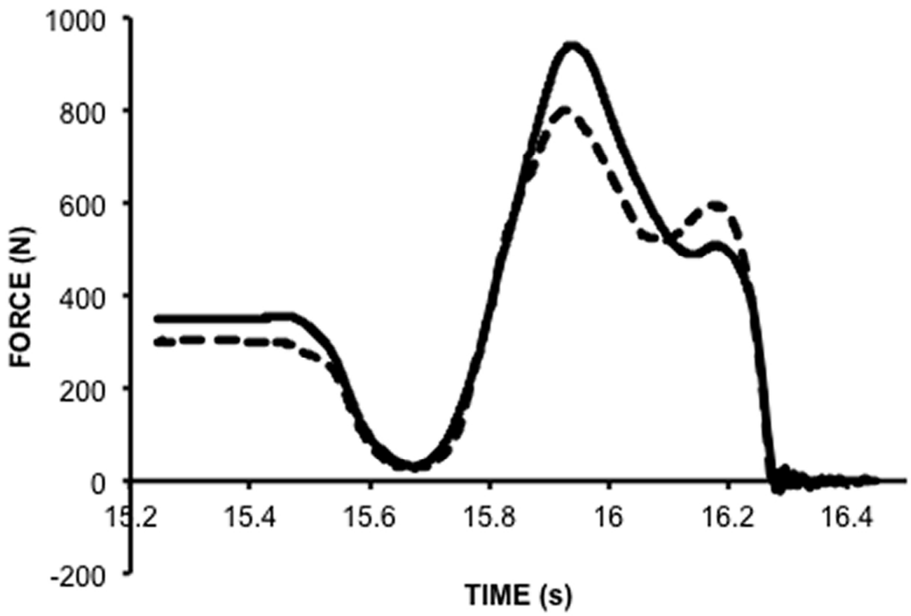

FIGURE 2. Force-time tracing for an ACL-R skier obtained during a countermovement jump demonstrating a shift in directionality of the asymmetry throughout the jump. The dashed lined represents the uninjured limb and the solid line represents the ACL-R limb
56x40mm (600 x 600 DPI)

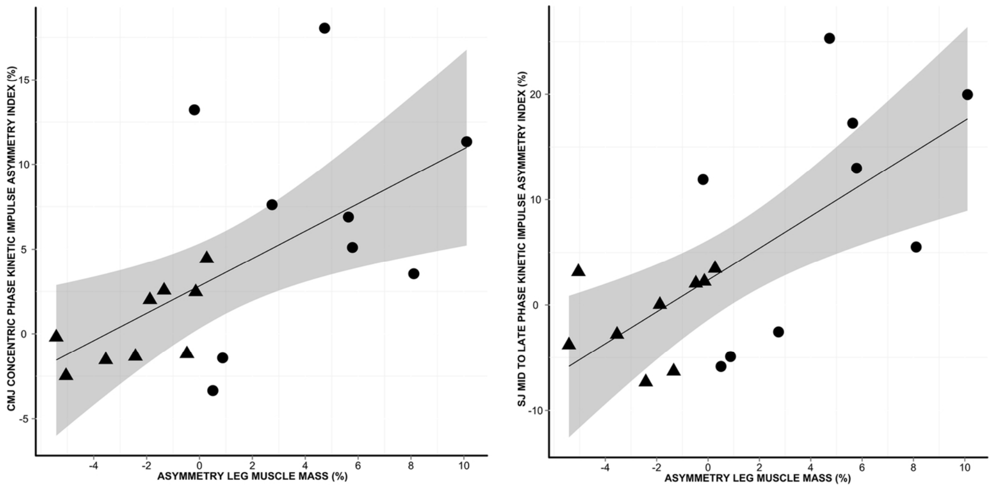

FIGURE 3. Left plot shows the relationship between the kinetic impulse asymmetry index for the concentric phase of the countermovement jump (CMJ) and asymmetry in leg muscle mass ($r = 0.57$; $F(1, 16) = 8.7$, $P < 0.01$). Right plot shows relationship between the kinetic impulse asymmetry index for Phase 2 of the squat jump (SJ) and asymmetry in leg muscle mass ($r = 0.66$; $F(1,16) = 13.64$, $P < 0.01$). Circles denote ACL-R skiers and triangles denote uninjured skiers. Shaded zone indicates the 95% confidence interval.
67x36mm (600 x 600 DPI)