Scand J Med Sci Sports 2015: 25: e301–e309
doi: 10.1111/sms.12314

SCANDINAVIAN JOURNAL OF
MEDICINE & SCIENCE
IN SPORTS

Lower limb asymmetry in mechanical muscle function: A comparison between ski racers with and without ACL reconstruction

M. J. Jordan[1], P. Aagaard[2], W. Herzog[1]

[1]Human Performance Laboratory, The University of Calgary, Calgary, Alberta, Canada, [2]Department of Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense M, Denmark
Corresponding author: Matthew J. Jordan, MSc, Canadian Sport Institute-Calgary, 2500 University Drive NW, Calgary, Alberta T2N 1N4, Canada. Tel: (403) 714-4655, Fax: (403) 282-6972, E-mail: mjordan@ucalgary.ca

Accepted for publication 30 July 2014

Due to a high incidence of anterior cruciate ligament (ACL) re-injury in alpine ski racers, this study aims 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 (AIs) for kinetic impulse (CMJ and SJ phase-specific kinetic impulse AI). Dual x-ray absorptiometry scanning was used to assess asymmetry in lower body muscle mass. Compared with 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 AI as a part of a multifaceted approach for improving outcome following ACL-R in elite ski racers.

Elite alpine ski racing (i.e., FIS World Cup, World Championship, and Olympic level racing) occurs at high speeds and in an unpredictable environment with repeated bidirectional turning composed of forceful concentric but predominantly eccentric movements that elicit near maximal levels of lower body muscle activation (Berg et al., 1995; Hintermeister 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 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 loss 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 different 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 commonly found in field sports 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 (Berchuck et al., 1990; Noyes et al., 1991; Salem et al., 2003; Tsepis et al., 2006; Paterno et al., 2007; Castanharo et al., 2011; Krishnan & Williams, 2011; Holsgaard-Larsen et al., 2014).

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 2 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., 2014) 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 vs 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).

To assess ACL-R skiers, it is important that functional neuromuscular testing be multifaceted and reflects the demands of ski racing, which includes repeated bilateral eccentric/concentric movements (Berg et al., 1995; Hintermeister 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 (AI) in uninjured and ACL-R elite ski racers and asymmetry in lower limb muscle mass measured with dual x-ray absorptiometry (DXA) scanning. We hypothesized that ACL-R ski racers would display significantly greater CMJ and SJ phase-specific kinetic impulse AIs compared with 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 and 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 (MCL) 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 preseason testing at the start of the off-snow training period. However, DXA scanning and the CMJ and SJ phase-specific kinetic impulse AI 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 DXA scanning. Following DXA scanning, subjects performed a standardized warm-up including 10 min 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 10 repetitions of dynamic stretching with a 2-s hold in the stretched position.

Subjects then performed 10 maximal CMJs where they were instructed to descend rapidly to a knee joint angle of 90-degree knee flexion and ascend maximally while keeping the hands firmly placed on the hips. Subjects were given a 5-min rest interval, which was followed by 10 maximal SJs. For the SJs, subjects were instructed to descend slowly to a knee joint angle of 90-degree knee flexion and remain stationary for 3 s. 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 the 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 10 jumps.

Force plate analysis

Subjects performed the CMJs and SJs on a dual force plate system (Model No: PS 2142; Pasco Canada, Oakville, ON, Canada) 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; Mathworks, Natick, MA, USA) according to procedures described elsewhere (Caserotti et al., 2001; Thorlund et al., 2008; Jakobsen et al., 2012). Briefly, the velocity of the body center 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 (Fig. 1). The total kinetic impulses for the right and left limb were then calculated separately for the eccentric

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
	Female	4	21 ± 1.4	66.8 ± 4.5	15.3 ± 2.5	NA	45.2 ± 3.8	43.5 ± 5.0
Uninjured skiers	Male	5	23.4 ± 2.5	80.7 ± 1.7	13.8 ± 2.2	NA	52.7 ± 4.9	52.3 ± 4.3

ACL-R, anterior cruciate ligament reconstruction; CMJ, countermovement jump; SJ, squat jump.

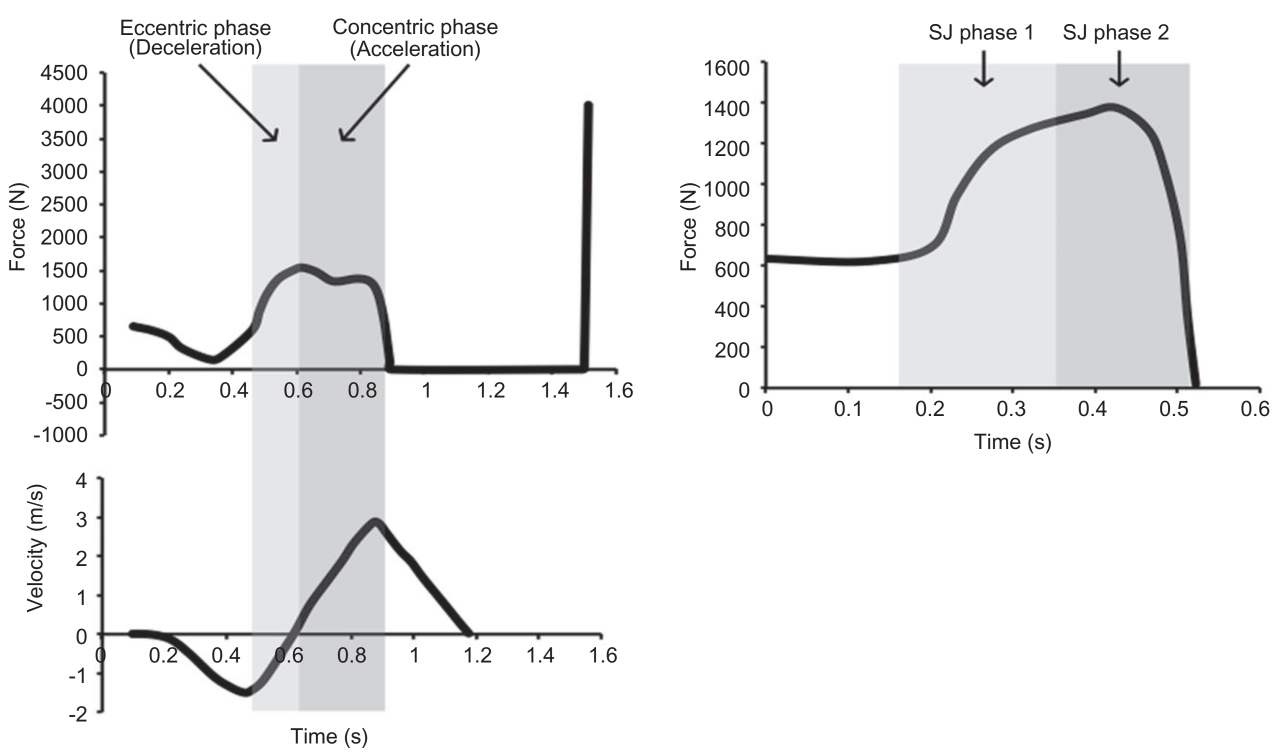

Fig. 1. Plots on the left identify the countermovement jump (CMJ) eccentric deceleration phase and concentric phase using the velocity of the body center of mass. Plot on the right side identifies squat jump (SJ) phase 1 (time = 0 to time = ½ of total jump time) and phase 2 (time = ½ of total jump time to takeoff).

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 (Fig. 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 limbs. 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 Fig. 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, Massachusetts, USA). The same technician performed the analysis for all the DXA scans.

Asymmetry index calculation

The CMJ and SJ phase-specific kinetic impulse AI 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

$$\text{Asymmetry index} = \frac{(\text{Left limb impulse} - \text{Right limb impulse})}{(\text{Maximum of left and right impulse})} \times 100 \quad [1]$$

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

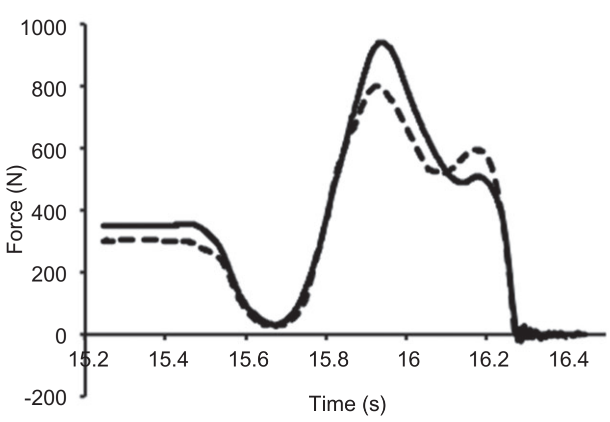

Fig. 2. Force–time tracing for an anterior cruciate ligament reconstruction (ACL-R) skier obtained during a countermovement jump demonstrating a shift in directionality of the asymmetry throughout the jump. The dashed lined represents the uninjured limb and the solid line represents the ACL-R limb.

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

$$\text{Asymmetry index} = \frac{(\text{Uninjured limb impulse} - \text{ACL-R limb impulse})}{(\text{Maximum of left and right impulse})} \times 100 \quad [2]$$

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% ($\beta = 0.80$) in the primary outcome variables. We expected to find a 10% difference in the kinetic impulse AI 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 AI 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 AI in leg muscle mass and the AI CMJ and SJ phase-specific kinetic impulse AI. Statistical analysis was carried out using R (Version 0.97.551; R Studio, Boston, MA, USA). All data are reported as the mean value ± 1 SD, unless otherwise stated. A statistical significance level of $\alpha = 0.05$ was chosen.

Results

ACL-R ski racers showed greater AI compared with 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 limbs 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

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 anterior cruciate ligament reconstruction (ACL-R) skiers

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

*$P < 0.05$; **$P < 0.001$.

Table 3. Data on countermovement jump (CMJ) and squat jump (SJ) phase-specific kinetic impulses for right and left limbs in anterior cruciate ligament reconstruction (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 (N·s)	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 (N·s)	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 (N·s)	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 (N·s)	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	11 519.2 ± 1945.3	12 022.8 ± 1720.4	10 981.6 ± 548.9	11 285.3 ± 453.4

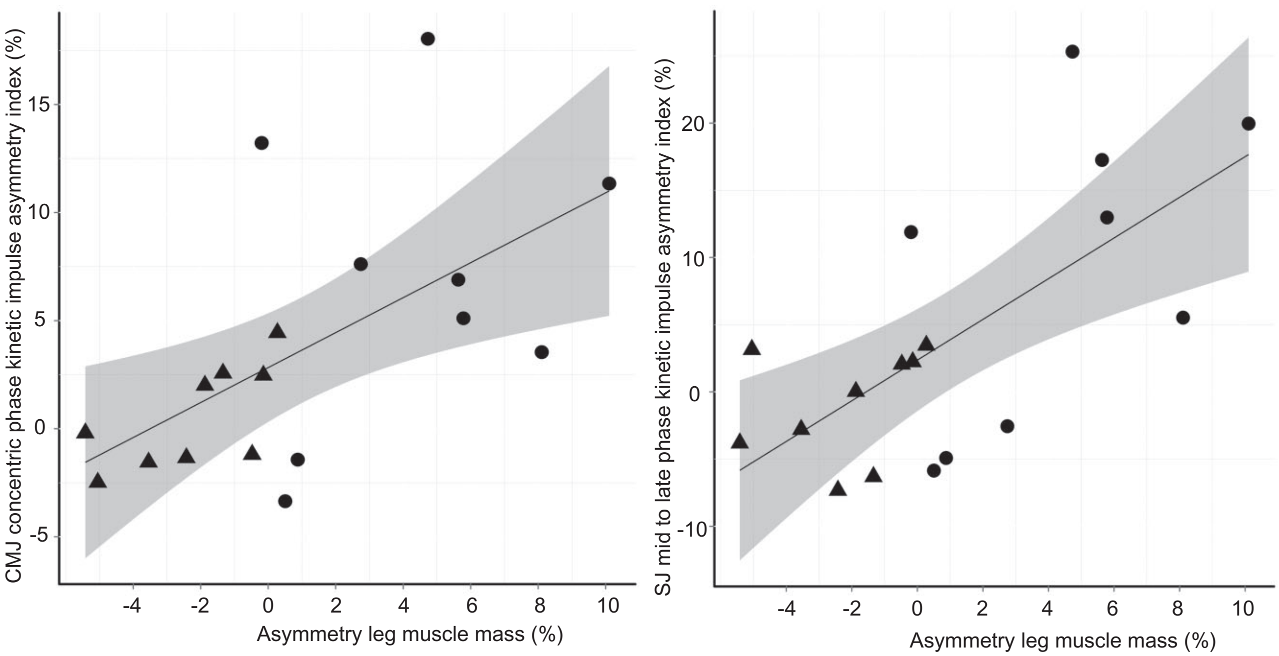

Fig. 3. Left plot shows the relationship between the kinetic impulse asymmetry index for the concentric phase of the countermovement jump (CMJ) and asymmetry in leg muscle mass [$r = 0.57$; $F(1,16) = 8.7$, $P < 0.01$]. Right plot shows relationship between the kinetic impulse asymmetry index for phase 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.

CMJ and SJ kinetic impulse AI and AI 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 [$r = 0.66$; $F(1,16) = 13.64$, $P < 0.01$] (Fig. 3). Additionally, large inter-individual variation was observed in the directionality of the CMJ phase-specific kinetic impulse AI 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 that 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 AI). The CMJ and SJ phase-specific kinetic AI 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 (Berg et al., 1995; Hintermeister 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 vs concentric muscular actions (Aagaard, 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 AI in top-level ski racers with a history of ACL-R compared with 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., 2014) even up to 2 years post-surgery (Paterno et al., 2007; Castanharo et al., 2011).

However, the CMJ and SJ phase-specific kinetic impulse AI 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 AI 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 (AI 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 AI.

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 = 0.5–2.2%). 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 AI, ski performance, and risk for injury is unknown. However, due to the bidirectional nature of ski racing and the large quadriceps muscle loading (Berg et al., 1995; Hintermeister 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 with 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 AI 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 AI as this athlete had the greatest asymmetry in the mid- to late phase of the SJ (AI of 25.3%), the CMJ concentric phase (AI of 18.0%), and the CMJ eccentric deceleration phase (AI 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, 2005; Donelly et al., 2012; Taylor & Waxman, 2013). Despite the potential relevance for including the CMJ and SJ phase-specific kinetic impulse AI as a part of a multifaceted 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 with uninjured ski racers, reflecting deficits in the affected limb (Tsepis et al., 2006; Krishnan & Williams, 2011; Konishi et al., 2012). However, while Konishi et al. (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 skiers 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 AI 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 AI in leg muscle mass and the kinetic impulse AI 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 (Krishnan & 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 7-year age difference between the ACL-R male and uninjured male racers, 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 AI and DXA scanning were only recently introduced into the annual preseason 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 AI 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 with uninjured ski racers. For both of these jump phases, the kinetic impulse AI reflected deficits in the affected limb. In addition, ACL-R ski racers also displayed greater asymmetry in leg muscle mass compared with 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 AI and the AI 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 AI as a part of a multifaceted 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 AI. 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 with uninjured ski racers despite a full return to sport. Further research using prospective study designs is required to evaluate the use of this functional asymmetry assessment as a part of a multifaceted approach for return to sport screening following ACL injury in elite ski racers.

Key words: Knee injury, vertical jump, injury prevention, return to sport screening.

Acknowledgements

Funding from the University of Calgary, Eyes High Doctoral Research Excellence Award and Own the Podium, was received for this work.

References

Aagaard P. Training-induced changes in neural function. Exerc Sport Sci Rev 2003: 31 (2): 61–67.

Berchuck M, Andriacchi T, Bach B, Reider B. Gait adaptations by patients who have a deficient anterior cruciate ligament. J Bone Joint Surg Am 1990: 72 (6): 871–877.

Bere T, Florenes TW, Krosshaug T, Koga H, Nordsletten L, Irving C, Müeller E, Reid RC, Senner V, Bahr R. Mechanisms of anterior cruciate ligament injury in world cup alpine skiing: a systematic video analysis of 20 cases. Am J Sports Med 2011: 39 (7): 1421–1429.

Bere T, Flørenes TW, Nordsletten L, Bahr R. Sex differences in the risk of injury in World Cup alpine skiers: a 6-year cohort study. Br J Sports Med 2014: 48 (1): 36–40.

Berg H, Eiken O, Tesch P. Involvement of eccentric muscle actions in giant slalom racing. Med Sci Sports Exerc 1995: 27 (12): 1666–1670.

Bobbert MF, Van Soest AJ. Why do people jump the way they do? Exerc Sport Sci Rev 2001: 29 (3): 95–102.

Caserotti P, Aagaard P, Simonsen EB, Puggaard L. Contraction-specific differences in maximal muscle power during stretch-shortening cycle movements in elderly males and females. Eur J Appl Physiol 2001: 84 (3): 206–212.

Castanharo R, Luz BS, Bitar AC, D’Elia CO, Castropil W, Duarte M. Males still have limb asymmetries in multijoint movement tasks more than 2 years following anterior cruciate ligament reconstruction. J Orthop Sci 2011: 16 (5): 531–535.

Dai B, Butler RJ, Garrett WE, Queen RM. Using ground reaction force to predict knee kinetic asymmetry following anterior cruciate ligament reconstruction. Scand J Med Sci Sports 2013: doi: 10.1111/sms.12118.

Donelly CJ, Elliott BC, Ackland TR, Doyle TL, Beiser F, Finch CF, Cochrane JL, Dempsey AR, Lloyd DG. An anterior cruciate ligament injury prevention framework: incorporating the recent evidence. Res Sports Med 2012: 20 (3): 239–262.

Ernst G, Saliba E, Diduch D. Lower-extremity compensations following anterior cruciate ligament reconstruction. Phys Ther 2000: 80 (3): 251–260.

Fitzgerald G, Axe M, Snyder-Mackler L. A decision-making scheme for returning patients to high-level activity with nonoperative treatment after anterior cruciate ligament rupture. Knee Surg Sports Traumatol Arthrosc 2000: 8: 76–82.

Flørenes TW, Bere T, Nordsletten L, Heir S, Bahr R. Injuries among male and female world cup alpine skiers. Br J Sports Med 2009: 43 (13): 973–978.

Granan L, Inacio M. Sport-specific injury pattern recorded during anterior cruciate ligament reconstruction. Am J Sports Med 2013: 41 (12): 2814–2818.

Herzog W, Nigg B, Read L, Olsson E. Asymmetries in ground reaction force patterns in normal human gait. Med Sci Sports Exerc 1989: 21 (1): 110–114.

Hewett TE. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am J Sports Med 2005: 33 (4): 492–501.

Hiemstra LA, Webber S, MacDonald PB, Kriellaars DJ. Knee strength deficits after hamstring tendon and patellar tendon anterior cruciate ligament reconstruction. Med Sci Sports Exerc 2000: 32 (8): 1472–1479.

Hintermeister RA, O’Connor D, Dillman CJ, Suplizio CL, Lange GW, Steadman RJ. Muscle activity in slalom and giant slalom. Med Sci Sports Exerc 1995: 27 (3): 315–322.

Holsgaard-Larsen A, Jensen C, Mortensen NHM, Aagaard P. Concurrent assessments of lower limb loading patterns, mechanical muscle strength and functional performance in ACL-patients: a cross-sectional study. Knee 2014: 10 (1): 66–73.

Impellizzeri FM, Rampinini E, Maffiuletti N, Macrora SM. A vertical jump force test for assessing bilateral strength asymmetry in athletes. Med Sci Sports Exerc 2007: 39 (11): 2044–2050.

Jakobsen MD, Sundstrup E, Randers MB, Kjær M, Andersen LL, Krustrup P. The effect of strength training, recreational soccer and running exercise on stretch-shortening cycle muscle performance during countermovement jumping. Hum Mov Sci 2012: 31 (4): 970–986.

Konishi Y, Oda T, Tsukazaki S, Kinugasa R, Fukubayashi T. Relationship between quadriceps femoris muscle volume and muscle torque at least 18 months after anterior cruciate ligament reconstruction. Scand J Med Sci Sports 2012: 22 (6): 791–796.

Krishnan C, Williams GN. Factors explaining chronic knee extensor strength deficits after ACL reconstruction. J Orthop Res 2011: 29 (5): 633–640.

van Mechelen W, Hlobil H, Kemper HCG. Incidence, severity, aetiology and prevention of sports injuries: a review of concepts. Sports Med 1992: 14 (2): 82–99.

Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase. J Orthop Sports Phys Ther 2006: 36 (6): 385–402.

Neumayr G, Hoertnagl H, Pfister R, Koller A, Eibl G, Raas E. Physical and physiological factors associated with success in professional alpine skiing. Int J Sports Med 2003: 24 (8): 571–575.

Nigg S, Vienneau J, Maurer C, Nigg BM. Development of a symmetry index using discrete variables. Gait Posture 2013: 38 (1): 115–119.

Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. Am J Sports Med 1991: 19 (5): 513–518.

Paletta GA, Levine DS, O'Brien SJ, Wickiewicz TL, Warren RF. Patterns of meniscal injury associated with acute anterior cruciate ligament injury in skiers. Am J Sports Med 1992: 20 (5): 542–547.

Palmieri-Smith RM, Thomas AC, Wojtys EM. Maximizing quadriceps strength after ACL reconstruction. Clin Sports Med 2008: 27 (3): 405–424.

Paterno MV, Ford KR, Myer GD, Heyl R, Hewett TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. Clin J Sport Med 2007: 17 (4): 258–262.

Patterson C, Raschner C, Platzer HP. Power variables and bilateral force differences during unloaded and loaded squat jumps in high performance alpine ski racers. J Strength Cond Res 2009: 23 (3): 779–787.

Pujol N, Blanchi MPR, Chambat P. The incidence of anterior cruciate ligament injuries among competitive alpine skiers: a 25-year investigation. Am J Sports Med 2007: 35 (7): 1070–1074.

Raschner C, Platzer HP, Patterson C, Werner I, Huber R, Hildebrandt C. The relationship between ACL injuries and physical fitness in young competitive ski racers: a 10-year longitudinal study. Br J Sports Med 2012: 46 (15): 1065–1071.

Salem GJ, Salinas R, Harding FV. Bilateral kinematic and kinetic analysis of the squat exercise after anterior cruciate ligament reconstruction. Arch Phys Med Rehabil 2003: 84 (8): 1211–1216.

Stevenson H, Webster J, Johnson RJ, Beynnon BD. Gender differences in knee injury epidemiology among competitive alpine ski racers. Iowa Orthop J 1998: 18: 64–66.

Taylor J, Waxman J. Evaluation of the effectiveness of anterior cruciate ligament injury prevention programme training components: a systematic review and meta-analysis. Br J Sports Med 2013: doi: 10.1136/bjsports-2013-092358. [Epub ahead of print].

Thorlund JB, Michalsik LB, Madsen K, Aagaard P. Acute fatigue-induced changes in muscle mechanical properties and neuromuscular activity in elite handball players following a handball match. Scand J Med Sci Sports 2008: 18 (4): 462–472.

Tsepis E, Vagenas G, Ristanis S, Georgoulis AD. Thigh muscle weakness in ACL-deficient knees persists without structured rehabilitation. Clin Orthop Relat Res 2006: 450: 211–218.

Westin M, Alricsson M, Werner M. Injury profile of competitive alpine skiers: a five-year cohort study. Knee Surg Sports Traumatol Arthrosc 2012: 20: 1175–1181.