A RETURN TO SKIING ENVELOPE OF FUNCTION FOR ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTED ELITE ALPINE SKI RACERS

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INTRODUCTION

Elite alpine ski racing comprises bidirectional turning with forceful concentric but predominantly eccentric contractions that create large quadriceps muscle loading and hamstrings/quadriceps muscle co-contraction (4, 10). Ski racing also occurs in an unpredictable environment where skiers are at an increased risk for lower body injury, especially to the knee joint and the anterior cruciate ligament (ACL) (2, 3, 8, 15). Unlike field sports, there are no sex-differences in ACL injury rates due to the preclusion of sex-related risk factors resulting from the large forces and unique mechanisms of ACL injury (8, 15).

Following ACL reconstruction (ACLR), the primary objective is to restore neuromuscular function by eliminating hamstrings/quadriceps strength deficits and increasing lower body functional symmetry in multi-joint movements (12, 14). However, long-term deficits often persist (9, 14), which is highly relevant for ACLR ski racers considering uninjured ski racers possess marked bilateral strength symmetry and high levels of hamstrings/quadriceps strength (13).

Assessing function and strength in the late-phase of rehabilitation when athletes are returning to sport is critical for re-injury prevention (12). This assessment is important for ski racers due to the high ACL re-injury rate (14) and the general risk for serious traumatic injury (2, 8). In order to better guide the late phases of rehabilitation, an “envelope of knee function” has been proposed as a conceptual framework to assess ACLR subjects, which includes a load and frequency of loading variable (7). However, no such frameworks have been developed and tested for the ACLR ski racer. In other sports, assessment of the ACLR athlete is a multi-stage process that includes hamstrings/quadriceps strength assessments and functional symmetry assessment in single leg and double leg movements (12), along with known risk factors for ACL injury, which for ski racers includes diminished core strength and lower body reactive strength (16). Reduced hamstring strength has also been cited as a potential risk factor for ski related ACL injury (11). Additionally, such a framework should reflect the demands of alpine ski racing that include repeated forceful eccentric/concentric movements, high force eccentric movements, large quadriceps loading and the ability to attenuate forces in a fatigued state (2, 4, 10, 13). With this knowledge, a ski-specific envelope of function can be developed that includes a multi-faceted approach to neuromuscular screening in the late phases of rehabilitation when athletes are returning to skiing.

While there are several variables of interest in a ski-specific envelope of function we chose to focus on hamstrings/quadriceps strength and functional asymmetry assessment in eccentric and concentric movements. There are several methods to assess hamstrings/quadriceps strength (9), but only isometric dynamometry permits the assessment of explosive strength (i.e. rapid rate of torque development: RTD) and maximal muscle strength (1, 17). Due to the short time course over which ACL injuries occur in ski racing (< 200 ms) (3), and the dynamic nature of the early turn phase (10), hamstrings/quadriceps explosive strength is important for the ACLR ski racer. Additionally, hamstrings/quadriceps explosive strength has been proposed for its relevance in ACL injury situations (17).

To assess functional symmetry, variants of the vertical jump have been used (12). As ski racing includes eccentric/concentric movements, assessing functional asymmetry in the countermovement jump (CMJ) is of interest due to the involvement of eccentric/concentric actions in this jump type. Additionally, by assessing asymmetry in the squat jump (SJ) the late phase of the jump can be used to detect deficits in knee extensor joint power (6). Using a dual force plate system the force-time curve can be analyzed to obtain these jump phases (5), and an asymmetry index (AI) can be calculated by evaluating the kinetic impulse over each jump phase (phase-specific kinetic impulse asymmetry index). This permits a highly objective and ski-specific assessment of functional asymmetry.

Based on the literature, ski-specific neuromuscular screening is required to help guide the late phase of rehabilitation and return to skiing for the ACLR skier. Screening can be considered conceptually as assessing an envelope of function for ski racing. The first aim of our study was to develop a ski-specific clinical test of functional asymmetry to assess a component of the envelope of function for a ski racer that involves the ability to produce lower body force during eccentric and concentric movements. We then evaluated functional asymmetry with these tests in a group of actively competing ACLR elite ski racers and uninjured elite ski racers. Due to the importance of hamstrings/quadriceps strength for ski performance and the relationship between ACLR and thigh muscle strength deficits, a second aim was to assess hamstrings/quadriceps explosive strength and maximal strength in uninjured and actively competing ACLR elite alpine ski racers. We hypothesized that the phase-specific functional asymmetry index in the CMJ and SJ would reveal increased asymmetry in ACLR ski racers compared to uninjured ski racers. We also hypothesized that the injured limb of ACLR ski racers would display significant deficits in hamstrings/quadriceps explosive strength and maximal strength.

METHODS

CMJ / SJ Phase-Specific Kinetic Impulse Asymmetry Index

Five female skiers (Age=23.8±3.3 years; Mass=70.3±5.7 kg; Post-Op=28.4±13.5 months) and four male skiers (Age=30.5±2.1 years; Mass=86.6±9.9 kg; Post-Op=23.5±10.6 months) were recruited for the ACLR group, and four female skiers (Age=21.0±1.4; Mass=66.8±4.5) and five male skiers (Age=23.4±2.5; Mass=80.7±1.7 kg) served as controls for the uninjured group (ACLR: n=9; Uninjured: n=9). All subjects were actively competing and had received medical clearance for return to skiing.

After giving informed consent, dual-xray absorptiometry (DXA) scans were used to assess lower limb muscle mass. Following a short warm up, subjects performed ten maximal CMJs and ten maximal SJs. For the CMJs, subjects were instructed to descend rapidly to a knee joint angle of 90 degrees and to ascend maximally while keeping hands firmly placed on the hips. For the SJs, subjects descended to a knee joint angle of 90 degrees, maintained a three-second static position, and were then instructed to jump maximally while keeping hands on the hips.

All jumps were performed on a dual force plate system that simultaneously measured the vertical ground reaction force from the left and right limbs (Frequency = 500 Hz). Data was then exported and the CMJ was analyzed according to the procedures described elsewhere to determine the eccentric deceleration phase and concentric phase (5). The SJ was divided into two separate phases. Phase 1 was defined as the initiation of the jump (Time = 0) to the mid-point of the jump (Time = ½ of the total jump time). Phase 2 was defined as the time interval from the mid-point of the jump (Time = ½ of the total jump time) to takeoff. Integration of the force-time curve over the appropriate intervals was performed and used to calculate the asymmetry index, AI. AI was calculated for the uninjured group and ACLR group as:

AI Uninjured Group = [(Left Limb – Right Limb) / (Maximum[Left,Right])] * 100

AI ACLR = [(Unaffected Limb – ACL-R Limb) / (Maximum[Left,Right])] * 100,

such that a positive number would indicate left leg dominance for the uninjured skiers and unaffected limb dominance for the ACLR group. AI was calculated as a mean of 10 jumps per subject. A statistical significance level of α = 0.05 was chosen.

Hamstrings/Quadriceps Explosive Strength and Maximal Strength Assessment

Three males (Age=28.3±0.6; Mass=89.0±9.3; Post-op=19.3±1.2) and five females (Age=24.2±3.2; Mass=69.4±4.1; Post-op=28.4±13.5) were recruited for the ACLR group, and 13 males (Age=21.6±3.4; Mass=84.1±7.3) and eight females (Age=20.9±2.4; Mass=64.8±6.2) were recruited for the uninjured group (ACLR: n=8; Uninjured: n=21).

After a warm up, subjects performed three maximal voluntary contractions (MVC) of isometric knee extension and flexion with each repetition separated by 30 seconds, and a 60-second rest interval between movements (17). Subjects performed the contractions explosively, and were given strong verbal encouragement along with visual feedback. Raw torque (voltage) data was sampled at 1000 Hz and converted to torque (Nm). Contractile rate of torque development (RTD) was calculated from 0 to 50 ms (RTD_{50}) and 0 to 100 ms (RTD_{100}) to assess early phase explosive strength (initial RTD). RTD calculated from 0 to 150 ms (RTD_{150}) and 0 to 200 ms (RTD_{200}) were used to measure late phase explosive strength (late RTD) (1). MVC and RTD values were normalized to body mass for group comparisons (9), and a limb average was used to compare the uninjured skiers to the ACLR skiers (α = 0.05).

RESULTS

CMJ / SJ Phase-Specific Kinetic Impulse Asymmetry Index

The mean and 95% confidence interval (95% CI) for AI in the concentric phase of the CMJ was 6.8% (1.5% to 12%) for the ACLR group and 0.5% (-1.3% to 2.4%) for the uninjured group (P<0.05). AI was greater during the late phase of the SJ in the ACLR group (Mean AI = 8.8%, 95% CI = 0.1% to 17.6%) compared to the uninjured skiers (Mean AI = -1.0%, 95% CI = -4.2% to 2.2%) ($P<0.05$). There was no significant difference in the AI for the first phase of the SJ in the ACLR group (Mean AI = -2.6%, 95% CI = -11.3% to 6.2%) versus the uninjured skiers (Mean AI = 1.0%, 95% CI = -1.9% to 4.0%). Additionally, there was no significant difference for the eccentric deceleration phase of the CMJ in the ACLR skiers (Mean AI = 5.2%, 95% CI = -4.5% to 14.9%) versus the AI found in the uninjured group (Mean AI = 1.0%, 95% CI = -1.5% to 3.5%). However, significant inter-individual variation was noted in the directionality of the AI for the ACLR skiers. ACLR skiers also presented with significantly greater asymmetry in limb muscle mass (Mean AI = 4.3%, 95% CI = 1.5% to 7.0%) compared to the uninjured group (Mean AI = -2.2%, 95% CI = -3.8% to -0.6%) ($P<0.001$). Linear regression analysis examining the relationship between the asymmetry index in jump variables 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 [$r = 0.66$; $F(1,16) = 13.64$, $P < 0.01$].

Hamstrings/Quadriceps Explosive Strength and Maximal Strength Assessment

The mean (± 1 standard deviation) peak isometric knee extensor torque (MVC) for the injured limb (IL) in the ACLR skiers was 3.4±0.6 Nm/kg compared to 4.4±1.0 Nm/kg for the uninjured limb (UL) ($P<0.05$). Significant bilateral limb deficits were also found for quadriceps late phase explosive strength (RTD_{200}: IL = 13.4±3.4 Nm/kg/s vs. UL = 17.3±3.8 Nm/kg/s, $P<0.05$; RTD_{150}: IL = 15.7±4.2 Nm/kg/s vs. UL = 20.0±4.7 Nm/kg/s, $P<0.05$). Hamstrings MVC was lower on the IL (1.5±0.4 Nm/kg) compared to the UL (1.8±0.4 Nm/kg) ($P<0.05$), and significant deficits were also found for hamstrings late phase explosive strength (RTD_{200}: IL = 6.3±1.4 Nm/kg/s vs. UL = 7.2±1.9 Nm/kg/s, $P<0.05$; RTD_{150}: IL = 7.6±1.6 Nm/kg/s vs. UL = 8.7±2.4 Nm/kg/s, $P<0.05$).

Consistent with our hypothesis, the ACL-R limb demonstrated significant deficits in hamstrings and quadriceps muscle maximal strength compared to the limb average of the uninjured skiers (Extension MVC: IL = 3.4±0.6 Nm/kg vs. Uninjured Group = 4.1±0.5 Nm/kg, $P<0.01$; Flexion MVC: IL = 1.5±0.4 Nm/kg vs. Uninjured Group = 1.8±0.3 Nm/kg, $P<0.05$). Substantial deficits in quadriceps explosive strength were also found in the IL compared to the uninjured group ($P<0.05$) (Figure 1). No differences were found between the contralateral limb of the ACLR skiers and the limb average of the uninjured group.

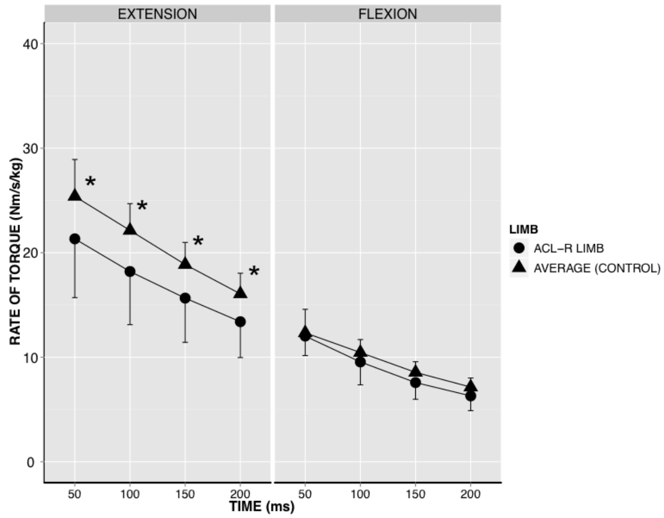

Figure 1. Quadriceps explosive strength and hamstrings explosive strength for the injured limb of the ACLR group compared to the limb average of the uninjured group (* P<0.05)

DISCUSSION

Functional neuromuscular screening previously has been used to evaluate ACLR athletes (12), and an envelope of knee function has been proposed and used as a conceptual framework for developing such tests (7). To date, there are no accepted approaches for assessing the elite alpine ski racer following ACLR. Such processes are important due to the high risk for non-contact skiing ACL injury (2, 8) and re-injury (15). An envelope of function for the ACLR ski racer returning to skiing should include known risk factors for ACL injury, such as diminished core strength, lower body reactive strength (16), and reduced hamstrings strength (11). It should also reflect the demands of ski racing including the requirement for large hamstrings/quadriceps strength (4, 10), high force eccentric movements and repeated concentric/eccentric movements (4). Additionally, due to the high risk for injury in the late phases of the ski race (2), performing such movements in a fatigued state should be considered within a ski-specific envelope of function.

As a first step towards developing ski-specific tests to assess an envelope of function in elite ski racers, we used a novel assessment of functional asymmetry during jumping (CMJ and SJ) and found increased asymmetry in the late phase of the CMJ and the concentric phase of the SJ. We did not find significant differences for the initial phase of the SJ or the eccentric deceleration phase of the CMJ. However, a single ACLR subject displayed a -16.1% asymmetry in the eccentric deceleration phase reflecting injured limb dominance. This observation emphasizes the importance of maintaining the directionality of the asymmetry index and the need to interpret the results of a functional asymmetry assessment on an individual basis due to the presence of inter-subject variation. The results also indicate that the phase-specific kinetic impulse asymmetry index using the CMJ and SJ was effective for detecting functional deficits in the ACLR elite ski racer, which suggests the relevance of these tests for assessing an envelope of knee function in the ACLR elite ski racer.

We also found significant bilateral limb deficits in hamstrings/quadriceps maximal strength and late phase explosive strength (RTD_{150} and RTD_{200}). Additionally, significant deficits in quadriceps maximal strength and explosive strength were found compared to the uninjured skiers. This is highly relevant to the elite ski racer due to the importance of hamstrings/quadriceps strength (4, 10, 11, 13), the association between ACLR and long-term deficits in quadriceps strength, and the relationship between minimizing deficits and successful return to activity (14).

Consistent with this perspective, one skier suffered a knee re-injury in the post-study period. Notably, this athlete presented with the largest functional asymmetry (CMJ Concentric AI = 18%; CMJ Concentric Phase AI = 20.5%; SJ Late Phase AI = 25.3%) and the second highest asymmetry in quadriceps MVC (36.9%). While this is a case example, it highlights the potential relevance of the proposed assessment techniques for identifying meaningful deficits in the ACLR ski racer.

In summary, a novel ski-specific test of functional asymmetry was developed to detect muscle mechanical deficits in the ACLR ski racer. Substantial functional asymmetry was found in actively competing ACLR elite ski racers despite full return to sport. Deficits in hamstrings/quadriceps explosive strength and maximal strength also were observed in this group. Within the context of a ski-specific envelope of function to assess the ACLR ski racer in the late phase of rehabilitation, it is possible that the two types of testing presented in the present study can be integrated as a part of a multi-faceted approach for improving outcome following injury.

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