

Rapid Hamstrings/Quadriceps Strength in ACL Reconstructed Elite Alpine Ski Racers

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ABSTRACT

Purpose: Due to the importance of hamstrings (HAM) and quadriceps (QUAD) strength for anterior cruciate ligament (ACL) injury prevention, and the high incidence of ACL injury in ski racing, HAM and QUAD maximal and explosive strength was assessed in ski racers with and without ACL reconstruction (ACL-R). **Methods:** Uninjured (n=13 males; n=8 females) and ACL-R (n=3 males; n=5 females; 25.0±11.3 months post-op) elite ski racers performed maximal voluntary isometric HAM and QUAD contractions to obtain maximal torque (MVC) and rate of torque development (RTD) at 0-50, 0-100, 0-150 and 0-200 ms. MVC and RTD (per kg body mass) were calculated for the uninjured group to compare between sexes, and to compare the control group with the ACL-R limb and unaffected limb of the ACL-R skiers. H/Q MVC and RTD strength ratios were also compared. **Results:** The ACL-R limb demonstrated significant HAM and QUAD deficits compared to the contralateral limb for MVC and late-phase RTD ($P<0.05$). Uninjured male skiers also displayed a limb difference for HAM MVC and RTD at 150 ms ($P<0.05$). QUAD MVC and RTD deficits were observed in the affected limb of ACL-R skiers, which led to an inflated H/Q Ratio (50 ms) compared to uninjured controls ($P<0.05$). Compared to male skiers, females displayed greater relative HAM RTD (50 ms) and elevated H/Q RTD Ratios (50 ms) suggesting enhanced ACL protection ($P<0.05$). **Conclusions:** Due to the strength demands of ski racing, our results suggest the importance of including HAM and QUAD strength assessments in the physical evaluation of uninjured skiers. Further, HAM and QUAD strength should be assessed over a long-term period following surgery to identify chronic strength deficits in ACL-R ski racers.

KEYWORDS: rate of force development, sex-differences, limb asymmetry, knee stability, knee injury prevention, knee rehabilitation, elite alpine skiing

INTRODUCTION

Paragraph #1: Elite alpine ski racing is a physically demanding sport involving high speeds and large external loads imposed on the lower limbs that occur in an unpredictable environment (8, 10, 17). Skiers perform repeated bidirectional turns with forceful eccentric muscle contractions, which typically involve maximal levels of neuromuscular activity in the thigh muscles (10, 17). To meet these demands, elite alpine ski racers display high levels of hamstrings and quadriceps strength, elevated hamstrings/quadriceps strength balance ratios and marked bilateral strength symmetry (24, 34).

Paragraph #2: Due to the extreme demands of elite alpine ski racing, there is a high risk for lower body injury, especially to the knee joint (11). In a competitive season, knee injuries accounted for over 30% of the injuries suffered by elite alpine ski racers, and more than half of these injuries resulted in a significant time loss from sport (> 28 days) (11). Anterior cruciate ligament (ACL) rupture is the most common form of serious knee joint injury in ski racing (11), accompanied by a high ACL re-injury rate (27). Research into the mechanisms and etiology of non-contact ACL injury in elite alpine ski racing highlights distinct differences compared to ACL injury in field sports, including several mechanisms of high force injury (8). Furthermore, at the elite level, no sex-differences in ACL injury rates are found, which is attributable to the preclusion of sex-related risk factors due to the high force/energy injury mechanisms (9, 11).

Paragraph #3: To achieve effective injury prevention, it is of importance to identify modifiable risk factors that can be targeted through exercise and training (36). However, to date, only a single scientific study has been conducted that was aimed at assessing the relationship between modifiable (trainable) risk factors and ACL injury in ski racers, suggesting that core strength deficits were associated with injury in young competitive ski racers (28). However, more senior

elite ski racers may be at even greater risk for ACL injury (27). Not only is there a paucity of scientific literature on trainable risk factors for ACL injury prevention in elite alpine ski racers, but also there are no studies on ACL re-injury prevention in actively competing ski racers with a history of previous ACL injury and ACL-reconstruction (ACL-R).

Paragraph #4: Following ACL injury, the primary objective is to restore quadriceps and hamstrings muscle strength. Thigh muscle strength deficits have been associated with successful return to sport and activity (6, 26). Restoring thigh muscle strength is especially important for ACL-R ski racers because of the importance of quadriceps strength in ski racing (10, 17), and the influence of hamstrings/quadriceps strength imbalance on knee injury risk (18, 24, 34). However, long-term hamstrings and quadriceps strength deficits often persist despite rehabilitation (3, 14, 26), and since coordinated hamstrings and quadriceps muscle function is important for ACL protection (5, 23, 30), identifying strength deficits is important.

Paragraph #5: Several measures of hamstrings and quadriceps muscle strength have been proposed for their clinical efficacy (1, 13, 38). However, due to the short time history of non-contact ACL injury in field sports (< 50 ms after foot contact) (22), the assessment of maximal hamstrings and quadriceps strength, which often requires more than 300 ms to develop under isometric conditions, has been questioned (38). Instead, the ratio of rapid isometric hamstring vs. quadriceps torque production (rate of torque development: RTD) assessed over shorter time frames (< 200 ms) has been proposed as a relevant measure of dynamic knee joint stabilization (38).

Paragraph #6: Explosive strength is quantified by the RTD during a maximal voluntary, isometric contraction (MVC) and can be separated into the rate of torque development observed in the very early phase of the MVC (0-100 ms), also denoted as the initial rate of torque

development (initial RTD), and the rate or torque development generated in the later phase of rising muscle force (late RTD), which is defined by the RTD developed from the onset of the MVC to a period between 100 and 200 ms (4). Additionally, the hamstrings/quadriceps strength ratio (H/Q Ratio) has been used to assess dynamic knee joint stabilization potential both in alpine ski racers (24, 34) and in other athlete populations (1, 38). Furthermore, as initial RTD, late RTD and maximum muscle strength are relevant to dynamic athletic performance and can be developed by specific training methods, assessment of these strength characteristics may provide important information for optimizing the design of rehabilitation and resistance training programs in ski racers returning from ACL injury (37).

Paragraph #7: Due to the unique characteristics of non-contact ACL injury in elite ski racers, the risk for ACL injury/re-injury, the importance of quadriceps and hamstrings muscle strength for ski performance and injury prevention, and the lack of scientific data on thigh muscle strength in actively competing elite ski racers with/without ACL injury, the aim of the present investigation was to perform a comprehensive hamstrings and quadriceps muscle strength assessment and to evaluate lower limb muscle mass in a group of actively competing elite alpine ski racers with/without ACL-R. We hypothesized that the ACL-R skiers would demonstrate significant deficits in the ACL-R limb for muscle mass, hamstrings strength and quadriceps strength, both compared to the contralateral limb and to the limb average of uninjured elite skiers (control group). Additionally, in uninjured individuals, we expected female skiers to demonstrate reduced thigh muscle strength compared to male skiers, and no signs of bilateral limb strength deficits in both genders.

METHODS

Subjects

Paragraph #8: Twenty-one uninjured skiers (Males: n=13; Females: n=8) from the Canadian Alpine Ski Team, including World Cup medalists, participated in this study, and were assessed at the start of the off-snow training period. Due to the challenges for subject recruitment in an elite athlete population, only eight actively competing ACL-R elite ski racers could be recruited (Males: n=3; Females: n=5), and a comparison between sexes was not made for this group. Of the eight ACL-R skiers, three received allografts and five were reconstructed with a semitendinosus autograft. Additionally, five of the eight ACL-R ski racers suffered injury on the non-dominant limb, and only a single subject sustained an isolated ACL injury. The pattern of secondary injury associated with the primary ACL injury was consistent with the reports from non-elite ski populations and included meniscus injury, medial collateral ligament injury and sub-chondral bone bruising (12, 25). Subject characteristics (Mean \pm 1SD) are provided in Table 1. All subjects had medical clearance for ski training and racing. Skiers 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. 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

Paragraph #9: Testing was undertaken as part of a routine annual pre-season fitness assessment, and all subjects were familiarized with the testing procedures. However, we were not able to obtain pre-injury testing data. After completing the informed consent, subjects were given a standardized 10-minute warm up on a Monarch cycle ergometer followed by light dynamic

stretching for the lower body muscles. Subjects were then seated in an isokinetic Biodex Dynamometer (System 3, Model 830-210) with the lateral epicondyle of the femur aligned with the axis of rotation of the dynamometer. Subjects were strapped to the dynamometer with two belts crossing the chest and one belt crossing the hips. The knee joint angle was set at 70 degrees of flexion (zero degrees was defined as full extension).

Paragraph #10: With the arms across the chest, subjects performed three MVCs of isometric knee extension and knee flexion for both the right and the left limbs (38). A short 30-second rest interval separated each trial and a 60-second rest interval separated each of the contractions. Subjects were instructed to perform the contractions as quickly and forcefully as possible and to maintain the contraction for two-seconds. Visual feedback was provided on-line using a computer monitor along with strong verbal encouragement. Trials with a noticeable countermovement were discarded and repeated. Torque data were sampled at 1000 Hz and collected using an external A/D converter (DATAQ Instruments, Windaq Data Acquisition Software Version 2.78) and stored on an IBM personal computer. Data were then exported into a custom-built software program for analysis (Matlab Version R2013a).

Data Analysis

Paragraph #11: Raw torque (voltage) signals were low-pass filtered using a 4th order zero-lag Butterworth filter (2). The raw voltage data were converted to torque (Nm) and gravity-corrected for the weight of the limb and dynamometer arm. The trial with the highest maximal torque was defined as the MVC and was selected for analysis (2). The start of the trial was defined as the time point when torque exceeded four percent of the MVC. Contractile rate of torque development (RTD) was obtained as the mean slope of the torque vs. time curve (i.e. $\Delta \text{Torque} / \Delta \text{Time}$, Nm/s) over the four distinct time periods (i.e. 0-50 ms; 0-100 ms; 0-150 ms; and 0-200

ms). RTD calculated between the time intervals of 0-50 ms (RTD₅₀) and 0-100 ms (RTD₁₀₀) were used to assess the initial RTD, and RTD calculated between the intervals of 0-150 ms (RTD₁₅₀) and 0-200 ms (RTD₂₀₀) were used to measure late RTD (4, 31). The H/Q Ratio was then calculated for the MVC and RTD as (38):

$$\text{MVC H/Q Ratio} = \text{Hamstrings MVC} / \text{Quadriceps MVC}$$

$$\text{RTD H/Q Ratio} = \text{RTD Hamstrings} / \text{RTD Quadriceps}.$$

MVC and RTD values were normalized to body mass for group comparisons (15). Additionally, a limb average was calculated for the uninjured skiers and compared separately to the unaffected limb and ACL-R limb of the ACL-R skiers (15, 32). Finally, relative RTD was calculated by normalizing RTD to the MVC (i.e. relative RTD = RTD / MVC) (2, 4, 13).

Body Composition

Paragraph #12: 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). Briefly, subjects were placed supine in the DXA scanner with the lower limbs extended and internally rotated and the upper limbs fully extended and pronated. Using the manufacturer's predefined procedures in the whole body scan mode, the lower body was partitioned by a horizontal line just proximal to the iliac crests and a centre line separating each lower limb. A diagonal line was drawn through the proximal edge of the femoral head and vertical lines were drawn on the lateral aspect of the lower limb tissue in order to capture all tissue in each of the lower limbs. A single experienced technician performed the data collection and analysis for all the DXA scans.

Statistical Analysis

Paragraph #13: 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% for our primary outcome measures ($\beta=0.80$). As our primary objective was to compare explosive strength and maximal thigh muscle strength in elite ski racers, and not all ACL-R subjects had sustained injury on the same leg, paired t-tests were used to assess within group differences, and a one way analysis of variance was used for between group comparisons. For between group comparisons, the body mass normalized limb average for the control group was compared to each limb of the ACL-R skiers, and the body mass normalized limb average was also used to compare uninjured male skiers with the uninjured female skiers. Statistical analysis was carried out using R (Version 0.97.551). All data were carefully assessed for normal distribution and equality of variance and, when required, data were transformed and retested to ensure that normality and homoscedasticity assumptions were satisfied. Non-transformed data are shown and all data are represented as the mean value \pm one standard deviation (SD), unless stated otherwise. Statistical significance was set at $\alpha = 0.05$.

RESULTS

Bilateral Limb Strength Comparisons

Paragraph #14: Consistent with our hypothesis, there were no significant bilateral differences in lower limb mass for the uninjured male skiers and the uninjured female skiers (Table 1). However, contrary to our expectations, ACL-R skiers did not display a significant bilateral limb difference in lower limb muscle mass. However, ACL-R skiers demonstrated significant deficits in hamstrings and quadriceps maximal strength (i.e. MVC) and late RTD (i.e. RTD₂₀₀ and RTD₁₅₀) in the ACL-R limb compared to the unaffected limb ($P<0.05$) (Table 2). As expected,

uninjured female skiers did not display significant bilateral limb differences across any of the hamstrings and quadriceps strength variables. While uninjured male skiers did not have a significant bilateral limb difference in quadriceps strength measures there was a 5% bilateral limb difference in hamstrings maximal strength ($MVC_{Right} = 1.91 \pm 0.25$ Nm/kg; $MVC_{Left} = 1.80 \pm 0.24$ Nm/kg, $P < 0.05$) and an 8% difference in hamstrings late RTD ($RTD_{150 Right} = 9.07 \pm 0.99$ Nm/s/kg; $RTD_{150 Left} = 8.35 \pm 1.07$ Nm/s/kg, $P < 0.05$).

Comparison of Limb Strength for Uninjured Males and Uninjured Females

Paragraph #15: In contrast with our hypothesis, there were no significant differences between uninjured males and uninjured females in maximal quadriceps or hamstrings strength (Extension MVC: Females = 3.96 ± 0.45 Nm/kg, Males = 4.17 ± 0.59 Nm/kg; Flexion MVC: Females = 1.66 ± 0.24 Nm/kg, Males = 1.86 ± 0.25 Nm/kg), and no differences in initial RTD or late RTD (Figure 1A). However, when normalized to the MVC, uninjured female skiers demonstrated significantly greater hamstrings relative RTD₅₀ ($P < 0.01$) and relative RTD₁₀₀ ($P < 0.05$) compared to the uninjured males (Figure 1B).

Comparison of Limb Strength for ACL-R Group and Uninjured Group

Paragraph #16: Consistent with our hypothesis, the ACL-R limb demonstrated significant deficits in hamstrings and quadriceps muscle maximal strength compared to the limb average for the uninjured skiers (Extension MVC: ACL-R Limb = 3.44 ± 0.63 Nm/kg vs. Uninjured = 4.09 ± 0.52 Nm/kg, $P < 0.01$; Flexion MVC: ACL-R Limb = 1.52 ± 0.40 Nm/kg vs. Uninjured = 1.78 ± 0.25 Nm/kg, $P < 0.05$). Significant quadriceps explosive strength deficits were also found in the ACL-R limb compared to the uninjured group ($P < 0.05$) (Figure 2A).

Paragraph #17: No differences in hamstrings muscle explosive strength were observed in the ACL-R limb compared to the uninjured group. However, relative RTD₅₀ (i.e. normalized to the

MVC) was found to be higher in the ACL-R limb compared to the uninjured skiers (Figure 2B) ($P<0.05$). Figure 2C provides a comparison of the hamstrings MVC torque for the ACL-R limb versus the contralateral limb, and the ACL-R limb versus the limb average of the uninjured skiers, as significant strength deficits were found in both instances.

Comparison of H/Q Ratios for Uninjured Males and Uninjured Females

Paragraph #18: A comparison of the H/Q Ratios between the uninjured female ski racers and uninjured males demonstrated a significant difference for only the H/Q Ratio₅₀ ($P<0.05$) (Figure 3A). As the H/Q Ratio can be elevated by diminished quadriceps strength (i.e. smaller denominator), Figure 3B illustrates the hamstrings and quadriceps RTD₅₀ for each subject in the uninjured male and uninjured female group, and is further stratified by subjects who demonstrated an H/Q Ratio₅₀ of less than 0.4, between 0.4 and 0.5 and above 0.5. Additionally, the plot is divided horizontally by those with a bilateral asymmetry in quadriceps maximal strength of less than 10% and greater than 10%. Only one female ski racer who is highlighted in the bottom right panel of Figure 3B presented with a high H/Q Ratio₅₀ (>0.5) and a bilateral asymmetry in quadriceps MVC of greater than 10% (individual bilateral asymmetry = 11.1%). Additionally, no significant differences were observed in bilateral quadriceps strength for the uninjured females or in comparison to the quadriceps strength of the uninjured males.

Comparison of H/Q Ratios for ACL-R Group and Uninjured Group

Paragraph #19: Contrary to our hypothesis, the ACL-R limb displayed an elevated H/Q Ratio₅₀ compared to the uninjured group ($P<0.05$) (Figure 3C). Figure 3D illustrates the hamstrings and quadriceps RTD₅₀ measured in the ACL-R limb for each of the ACL-R subjects. The plot is further divided to show subjects with an H/Q Ratio between 0.4 and 0.5, and those who presented with the highest H/Q Ratio (>0.6). As significant bilateral asymmetries were observed

in quadriceps maximal strength (MVC), the plot is further divided horizontally to show those subjects with a bilateral asymmetry in quadriceps maximal strength of less than 15%, between 15% and 25% and those with an asymmetry greater than 25%. The bottom right panel of Figure 3D identifies three subjects who presented with a high H/Q Ratio₅₀ (Range = 0.60-0.89) along with the largest bilateral asymmetry in quadriceps MVC reflecting deficits in the ACL-R limb. Furthermore, the ACL-R limb also demonstrated significant deficits in quadriceps explosive strength and maximal strength compared to the contralateral limb, and compared to the limb average of the uninjured group.

DISCUSSION

Comparison of Limb Strength for ACL-R Skiers and Uninjured Skiers

Paragraph #20: To the authors' knowledge, the present study was the first to evaluate quadriceps and hamstrings strength in actively competing elite alpine ski racers with/without ACL-R, and to also use isometric dynamometry to differentiate between maximal strength and explosive strength (i.e. rapid force development ability). Such investigations are important because of the high incidence of ACL injury and re-injury in this athlete population (8, 9, 11, 27). Despite the challenges in studying elite alpine ski racers (e.g. small sample size, availability, training periodization), specific research efforts are required in the population of interest in order to develop appropriate guidelines for return to sport and strategies aimed at injury prevention (36).

Paragraph #21: The main findings of this study were the presence of significant deficits in quadriceps maximal strength (MVC) and explosive strength (RTD) in the ACL-R limb of actively competing elite alpine ski racers compared to the contralateral limb, and compared to the limb average of uninjured elite alpine ski racers despite long post-operative periods (Mean =

25.0±11.3 months). Because of the substantial risk for injury (11), the importance of quadriceps muscle strength for ski performance (10, 17, 24), and the association between the restoration of quadriceps strength and successful return to activity (6, 26), the identification of quadriceps strength deficits is highly relevant for the ACL-R elite alpine ski racer.

Paragraph #22: Our results are consistent with previous findings where long-term deficits in quadriceps muscle strength have been identified in ACL-R subjects (14, 15, 21, 26, 35) and ACL deficient knees (3, 33). While there is evidence showing that quadriceps mass and strength is restored at 18 months post-surgery (19), some studies suggest a reduction in quadriceps muscle voluntary activation (35), and peripheral muscle factors (21) as contributors to deficits in quadriceps strength that are observed long after surgical reconstruction of the ACL. An investigation comparing quadriceps strength in physically active ACL-R subjects more than two years post-surgery with physically active controls found a 25% strength deficit in the ACL-R limb when torque was normalized to body mass (14). While the present investigation used isometric dynamometry and not isokinetic dynamometry, the mean difference in peak knee extensor torque was 14% in the ACL-R limb compared to the limb average of the control group. Furthermore, while Hiemstra et al. (2000) did not make bilateral comparisons in the ACL-R group due to the possibility of contralateral limb deficits, the results of the present study found no difference in quadriceps strength in the uninjured limb of the ACL-R skiers compared to the uninjured skiers.

Paragraph #23: We found significant bilateral limb deficits in quadriceps maximal strength in the injured limbs compared to the uninjured limbs in the ACL-R skiers (Mean Asymmetry = 19%). The implications of significant bilateral asymmetry in quadriceps maximal strength for ski performance and risk for ACL re-injury are unknown. However, uninjured ski racers display

marked bilateral symmetry in quadriceps strength (24), and are required to perform repeated bidirectional turns that involve large quadriceps muscle loading (10, 17). Consistent with Neumayr et al. (2003), the mean bilateral asymmetry in quadriceps maximal strength found for the uninjured skiers in the present study was less than 2%. This result suggests the importance of bilateral quadriceps strength symmetry for ski racers and the importance of restoring quadriceps strength following ACL-R in elite ski racers. Additionally, as these deficits were found in actively competing ski racers, it also provides a rationale for long-term monitoring of quadriceps strength post ACL-R in this population.

Paragraph #24: As ski racers regularly perform resistance training exercises to prepare for competition, the large bilateral asymmetry in quadriceps maximal strength may also be related to the exceptionally high torque values observed in the uninjured limbs (Extensor MVC: Males = 417.8 ± 17.3 Nm, Females = 291.7 ± 57.7 Nm), which are considerably higher than the torques observed for the uninjured limb in physically active ACL-R subjects (19) and in untrained ACL-R subjects (35). We did not include information on the type of resistance exercise performed by the subjects in our study. However, the findings of large between-limb strength discrepancies may warrant further investigation into the use of specific resistance training strategies, such as the long-term utilization of unilateral lower body movements, to address strength deficits in the ACL-R limb.

Paragraph #25: While the restoration of quadriceps strength is associated with successful return to activity in ACL-R non-skiers (6, 26), this has not been demonstrated in ACL-R elite ski racers. However, in the present cohort of ACL-R skiers, one subject sustained an injury to the contralateral medial collateral ligament during the study period. Notably, this athlete had the second highest asymmetry in quadriceps maximal strength (36.9%). A second ACL-R athlete

retired due to limitations from the knee injury one World Cup season following the study period. This particular subject had the largest asymmetry in quadriceps maximal strength (54.2%). While these examples are case related and hence do not provide strict scientific support for a causality between deficits in quadriceps maximal strength and successful return to skiing following ACL-R, it suggests the potential relevance for future investigation into the relationship between quadriceps strength deficits and successful return to pre-injury performance levels following ACL-R.

Paragraph #26: In addition to the bilateral deficits observed in quadriceps maximal strength, significant bilateral deficits in quadriceps explosive strength (RTD₁₅₀ and RTD₂₀₀) were also found in the injured limb of ACL-R ski racers compared to their uninjured limb and compared to the limb average of the uninjured group. As non-contact ACL injuries in ski racing occur in time frames less than 200 ms (8) and the re-loading of the contralateral limb during bidirectional turning in the technical events (slalom and giant slalom) occurs in approximately 150 ms (17), explosive strength may be important for elite ski racers. Furthermore, as explosive strength and maximal strength are distinct abilities, and trained with different forms of resistance training exercise (2, 4, 37), the identification of specific quadriceps strength deficits may be important for the ACL-R elite alpine ski racer in order to attain pre-injury performance levels.

Paragraph #27: While no bilateral limb differences were observed for the early phase of quadriceps torque development (RTD₅₀ and RTD₁₀₀), the ACL-R limb still demonstrated lower values than the uninjured group. The early phase of torque development in an isometric contraction is related to intrinsic muscle properties, such as fiber type composition and myosin heavy chain content, as well as to the pattern of initial motor neuron firing frequency (4). Due to the short time frame for non-contact ACL injury in field sports (22), assessing the early phase of

isometric torque development has also been proposed as a relevant measure of dynamic knee joint stabilization potential (38). As with the lack of evidence between increased bilateral limb asymmetry in quadriceps maximal strength and return to skiing performance in ACL-R skiers, there is currently no evidence relating deficits in early phase explosive strength (initial RTD) and ACL re-injury in elite alpine ski racers.

Paragraph #28: The injured limb of the ACL-R ski racers also displayed significantly lower hamstrings maximal strength compared to the uninjured group, and bilateral limb deficits in hamstrings maximal strength and late phase explosive strength compared to the uninjured limb. While there is an isolated report of a full restoration in hamstrings strength after semitendinosus autograft reconstruction (20), deficits in hamstrings strength have been observed in ACL-R subjects with semitendinosus autografts compared to uninjured controls (15), and compared to pre-operative levels two-years following ACL-R (14). Additionally, semitendinosus autograft reconstruction has been shown to elongate the knee flexor electromechanical delay, which may impair knee stabilization in injury situations (29). We were unable to recruit sufficient ACL-R skiers to control for the graft type, which is a limitation of the present investigation. However, five of the eight ACL-R ski racers obtained a semitendinosus autograft, which may partially explain the deficits in hamstrings muscle strength observed in this group of ACL-R ski racers.

Paragraph #29: Nevertheless, the hamstrings muscles act as an ACL agonist to resist anterior translation of the tibia relative to the femur (7, 23), which is relevant for ACL injury prevention in ski racing due to the existence of a unique injury mechanism involving anterior shear loads imposed upon the tibia (8, 27). Additionally, the hamstrings and quadriceps muscles act in a coordinative fashion for knee stabilization and ACL protection (3, 7, 23, 30, 31, 39). A relationship between deficits in hamstrings strength and ACL injury has been proposed in high

level skiers (18). However, no study has been conducted to evaluate the effects of ACL-R or graft-type on hamstrings strength deficits, and the corresponding risk for ACL re-injury in elite alpine racers. Given the high risk for ACL injury and an injury mechanism involving large anterior tibial shear loads, further research into this possibility is warranted.

Paragraph #30: An unexpected finding of this study was the greater relative RTD in the early phase of rising muscle force (0-50 ms) for the ACL-R limb compared to the uninjured group. Relative RTD, which involves normalization to the MVC, is often used as a qualitative measure of explosive strength and for differentiation between potential mechanisms underlying adaptations in explosive strength following resistance exercise (2, 13). However, it is important to consider absolute strength values in the interpretation of the relative RTD ratio. In the present study, the ACL-R limb had significantly lower maximal isometric knee flexor torques and no difference in RTD₅₀ compared to the uninjured group. As the lower MVC values reduced the magnitude of the denominator in the calculation of the relative RTD₅₀ ratio, this result should not be interpreted as a difference in the initial phase hamstrings explosive strength ability for the ACL-R skiers.

Comparison of Limb Strength for Uninjured Male Skiers and Uninjured Female Skiers

Paragraph #31: Non-contact ACL injury in elite alpine ski racing is unique in that no clear sex-related difference in ACL injury rates have been identified (9, 11, 27). This finding has been attributed to the preclusion of sex-related risk factors due to the large external forces experienced in ski racing (9, 11). Because of the large quadriceps loading and evidence of pronounced hamstrings/quadriceps co-contraction in skiing (10, 17), specific hamstrings and quadriceps strength requirements may exist for successful performance at the elite level for male and female ski racers (24). However, there are limited scientific investigations focusing on sex-differences

in thigh muscle strength in elite alpine ski racers. While male ski racers were reported to have greater absolute strength values than females assessed with isokinetic dynamometry (24), the use of absolute strength values may not be appropriate when comparing male and female subjects. Instead body mass normalization is recommended (15). In the present investigation, no sex-differences in hamstrings and quadriceps strength were found when corrected for body mass, which has been found elsewhere (15).

Paragraph #32: However, the uninjured female skiers had a greater relative RTD over the initial phase of the isometric MVC (relative RTD₅₀ and relative RTD₁₀₀) compared to the male skiers. As discussed above, the relative RTD ratio must be interpreted alongside absolute strength values because of the possibility of a reduced denominator resulting from deficits in the peak isometric hamstrings torques obtained during the MVC. However, no bilateral limb deficits were observed in hamstrings maximal strength (MVC) for the female ski racers, or in comparison to the uninjured males. Therefore, the greater relative RTD₅₀ and relative RTD₁₀₀ ratio may be evidence of a qualitative difference in explosive strength for the male and female skiers included in the present investigation. As we did not include other variables in our analysis that may affect relative RTD, such as physiological factors or type of resistance training exercise employed by the subjects (2, 4), we are unable to explain this finding.

Paragraph #33: Unexpectedly, while no bilateral limb differences in thigh muscle strength were found for the female skiers, the uninjured male ski racers displayed reduced hamstrings maximal strength (MVC) and late phase explosive strength (RTD₁₅₀) in the left compared to the right leg. While the mean deficit in hamstrings maximal strength was only 5.3%, this asymmetry was consistently biased in the male ski racers reflecting systematic right-limb dominance. Due to the importance of the hamstrings muscle in resisting anterior shear forces that load the ACL (7, 23),

and evidence of substantial hamstrings/quadriceps co-contraction during ski turns (17), the presence of bilateral limb deficits in hamstrings strength may be of concern for elite ski racers. Additionally, while a clear association between bilateral hamstrings strength deficits and ACL injury has not been made, hamstrings muscle strength has been put forth in the literature as a relevant metric for ACL injury prevention in ski racers (18, 24, 34). Taken alongside the limited scientific research in support of an association between hamstrings muscle strength and ACL injury, this finding warrants future study into the relationship between hamstrings muscle strength deficits and ACL injury. It also suggests that regular hamstrings muscle strength assessments be included in the evaluation of uninjured elite ski racers alongside other established risk factors for ACL injury in ski racing, such as the lower body reactive strength index and core strength (28).

H/Q Ratios in Uninjured Male Skiers, Uninjured Female Skiers and ACL-R Skiers

Paragraph #34: The H/Q Ratio has been purported as an important marker of dynamic knee joint stabilization potential for ACL injury prevention in alpine ski racers (24, 34) and in other populations (1, 16, 38). However, no direct scientific evidence exists linking a diminished H/Q Ratio with ACL injury rates in elite ski racers. Moreover, in a preliminary study, it was concluded that the H/Q Ratio was not predictive of ACL injury prevention in high-level skiers (18). Nevertheless, the H/Q Ratio is often reported in this population (24, 34). A study by Neumayr et al. (2003) found H/Q Ratios for elite ski racers ranging from 0.57 to 0.60 for isokinetic dynamometry, which limits a comparison to the present investigation due to the use of isometric dynamometry. In our study, explosive strength and maximal strength H/Q Ratios ranged between 0.42 to 0.55 for the uninjured female skiers and 0.45 to 0.47 for the uninjured male skiers.

Paragraph #35: Interestingly, the uninjured female ski racers demonstrated a higher H/Q Ratio₅₀ compared to the male ski racers (0.55 vs. 0.46, respectively). In order to interpret the H/Q Ratio, it is important to consider absolute strength values due to the possibility of an artificially inflated ratio resulting from deficits in quadriceps strength (i.e. reduced denominator) (40). However, in our post-hoc analysis, we evaluated the individual H/Q Ratios alongside bilateral limb asymmetry in quadriceps maximal strength (MVC). Of all the females presenting with the highest H/Q Ratios, only one had a bilateral asymmetry in quadriceps strength greater than 10% (individual asymmetry = 11%), and the mean bilateral limb asymmetry in quadriceps maximal strength for the remaining uninjured female skiers was 0.6%. Furthermore, the uninjured females did not present with bilateral limb deficits in quadriceps muscle maximal strength or explosive strength. Thus, we feel it is reasonable to conclude that there was no evidence of a reduction in quadriceps strength that may have contributed to an elevated H/Q Ratio.

Paragraph #36: Together with these observations, the elevated H/Q Ratio₅₀ found in the uninjured female skiers may indicate better hamstrings/quadriceps muscle strength balance over the initial phase of torque rise in the isometric MVC. While there are very limited reports using the explosive strength H/Q Ratio, our findings differ from those found in other female athlete populations (38). Again, the precise reason for this is unknown. However, as hamstring strength is often identified by experts as an important factor in non-contact ACL injury prevention for ski racers (18, 24, 34), it is possible that an increased emphasis on hamstrings strength development in ski racers contributed to the differences between the present investigation and the study performed by Zebis et al. (2011) in high level female soccer players. As we did not include information on the resistance training program employed by the subjects, we are unable to explain this finding.

Paragraph #37: To the authors' knowledge, there are no investigations that were aimed at evaluating the H/Q Ratio in actively competing ACL-R elite alpine ski racers, and no associations have been made between the H/Q Ratio and the risk for ACL re-injury. Hiemstra et al. (2004) found regional deficits in knee flexor and extensor strength in ACL-R subjects that led to an increased H/Q Ratio at small angles of knee flexion. In the present study, the affected limb of the ACL-R skiers demonstrated an elevated H/Q Ratio₅₀ compared to the uninjured skiers. However, due to the persistence of chronic quadriceps weakness in ACL-R subjects (3, 14, 15, 26, 33, 35), this result was interpreted alongside individual H/Q Ratios and absolute quadriceps strength values. In this perspective, three of the ACL-R ski racers with the highest H/Q Ratios (> 0.6) also had the largest deficits in quadriceps maximal strength (Asymmetry $> 25\%$). This finding is consistent with reports of others where an elevated H/Q Ratio in ACL-R subjects was attributed to deficits in quadriceps strength (40).

Paragraph #38: An elevated H/Q Ratio resulting from diminished quadriceps strength may indicate better hamstrings/quadriceps strength balance. However, as discussed previously, quadriceps strength deficits may be disadvantageous for elite alpine ski racers due to the bidirectional turns and large quadriceps muscle loading. Furthermore, while representing case examples, it should be reiterated that the three ACL-R ski racers presenting with the highest H/Q Ratios on the injured limb had the greatest bilateral limb deficits in quadriceps strength, and were also those individuals who were unable to make a full and safe return to skiing. Based on the present results, we suggest that the H/Q Ratio be interpreted with caution in ACL-R ski racers and alongside absolute hamstrings/quadriceps strength values to obtain a comprehensive assessment of hamstrings and quadriceps muscle strength.

CONCLUSION

Paragraph #39: In conclusion, we found substantial deficits in quadriceps maximal strength and explosive strength in the affected limb of actively competing ACL-R elite alpine ski racers compared to the contralateral limb and compared to uninjured ski racers. Deficits in hamstrings maximal strength and late phase explosive strength were also observed in the ACL-R limb. Unexpectedly, uninjured male ski racers displayed bilateral limb deficits in hamstrings maximal strength and late phase explosive strength. An increased relative RTD over the early phase of rise in isometric torque was found for the uninjured female skiers compared to uninjured male ski racers, whereas no sex-differences were observed in any of the other hamstrings or quadriceps explosive strength and maximal strength variables. However, there were limitations to the present investigation that included a relatively small sample size for the uninjured female group and ACL-R group. Additionally, due to limitations in recruiting subjects, we were unable to control for the graft type used in the ACL reconstruction.

Paragraph #40: Despite these limitations, we conclude that quadriceps and hamstrings maximal strength and explosive strength are important determinants for evaluating ACL-R ski racers and uninjured ski racers, and that these outcome measures should be included as a part of a comprehensive strength assessment in elite alpine ski racers. These evaluations should be undertaken over long post-surgical periods in ACL-R skiers, and should be continued even after full return to ski racing. As explosive strength and maximal strength are developed by specific resistance training methods, identifying such deficits may also assist in the design of rehabilitation and training programs for elite ski racers returning to skiing following ACL loss. Finally, while representing case examples, failure to regain quadriceps strength following ACL-R was associated with failure to make a full return to skiing. However, future studies must be

undertaken to confirm the possibility of a relationship between quadriceps strength deficits and return to skiing outcome. Additionally, future studies should also control for the graft-types used in ACL reconstruction, and further examine the relationship between graft-type, hamstrings strength loss and outcome following ACL-R. The relationship between hamstrings and quadriceps strength deficits, and return to skiing outcome, requires careful and systematic evaluation in ACL-R elite alpine ski racers in order to identify ski-specific strength thresholds that should be met following injury. It is hoped that in future longitudinal studies, these issues will be addressed, and assessments between hamstrings and quadriceps strength and ACL injury/re-injury in elite alpine ski racers will be made as a part of a multi-faceted approach to injury prevention, including other risk factors for non-contact ACL injury in ski racing.

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FIGURE CAPTIONS:

FIGURE 1. (A) Hamstrings and quadriceps rate of torque development (RTD) for uninjured male and uninjured female ski racers. (B) Hamstrings and quadriceps relative RTD (RTD/MVC) for uninjured male and uninjured female ski racers (* $P<0.05$; ** $P<0.01$).

FIGURE 2. (A) Hamstrings and quadriceps rate of torque development (RTD) for the affected limb of ACL-R skiers and limb average of controls (uninjured males and uninjured females). (B) Hamstrings and quadriceps relative RTD for the affected limb of ACL-R skiers and limb average of controls. (C) Bilateral comparison of hamstrings MVC in ACL-R skiers and controls (* Between Group Difference $P<0.05$; # Within Group Difference $P<0.05$).

FIGURE 3. (A) Ratio of hamstrings vs. quadriceps explosive strength (H/Q Ratio) for uninjured male and female ski racers. (B) Individual hamstrings and quadriceps rate of torque development at 50 ms (RTD₅₀) for male and female skiers, range in H/Q Ratio and asymmetry in quadriceps MVC. (C) H/Q RTD Ratio for the affected limb of ACL-R skiers and limb average of control group skiers. (D) Individual hamstrings and quadriceps RTD₅₀ for the ACL-R limb, range in H/Q Ratio and asymmetry in quadriceps MVC (* $P<0.05$).