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

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ABSTRACT

JORDAN, M. J., P. AAGAARD, and W. HERZOG. Rapid Hamstrings/Quadriceps Strength in ACL-Reconstructed Elite Alpine Ski Racers. *Med. Sci. Sports Exerc.*, Vol. 47, No. 1, pp. 109–119, 2015. **Purpose**: Because of 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 were 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 after operation) 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 kilogram 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. HAM/QUAD MVC and RTD strength ratios (H/Q ratios) were also compared. **Results**: The ACL-R limb demonstrated significant HAM and QUAD deficits compared with 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 with that in uninjured controls ($P < 0.05$). Compared with male skiers, females displayed greater relative HAM RTD (50 ms) and an elevated H/Q RTD ratio (50 ms), suggesting enhanced ACL protection ($P < 0.05$). **Conclusions**: Because of 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. Furthermore, HAM and QUAD strength should be assessed over a long-term period after surgery to identify chronic strength deficits in ACL-R ski racers.
Key Words: RATE OF FORCE DEVELOPMENT, SEX DIFFERENCES, LIMB ASYMMETRY, KNEE STABILITY, KNEE INJURY PREVENTION, KNEE REHABILITATION, ELITE ALPINE SKIING

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 (HAM) and quadriceps (QUAD) strength, an elevated HAM/QUAD strength ratio (H/Q ratio), and marked bilateral strength symmetry (24,34).

Because of 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 experienced by elite alpine ski racers, and more than half of these injuries resulted in a significant time loss from sport (>28 d) (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 reinjury rate (27). Research into the mechanisms and etiology of noncontact ACL injury in elite alpine ski racing highlights distinct differences compared with 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).

To achieve effective injury prevention, it is important 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 an 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,

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there are no studies on ACL reinjury prevention in actively competing ski racers with a history of ACL injury and ACL reconstruction (ACL-R).

After ACL injury, the primary objective is to restore QUAD and HAM muscle strength. Thigh muscle strength deficits have been associated with a 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 QUAD strength in ski racing (10,17) and the influence of HAM/QUAD strength imbalance on knee injury risk (18,24,34). However, long-term HAM and QUAD strength deficits often persist despite rehabilitation (3,14,26), and because coordinated HAM and QUAD muscle function is important for ACL protection (5,23,30), identifying strength deficits is important.

Several measures of HAM and QUAD muscle strength have been proposed for their clinical efficacy (1,13,38). However, because of the short time history of noncontact ACL injury in field sports (<50 ms after foot contact) (22), the assessment of maximal HAM and QUAD strength, which often requires more than 300 ms to develop under isometric conditions, has been questioned (38). Instead, the ratio of rapid isometric HAM versus QUAD 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).

Explosive strength is quantified by the RTD during a maximal voluntary isometric contraction (MVC) and can be separated into the RTD observed in the very early phase of the MVC (0–100 ms), also denoted as the initial RTD, and the RTD 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). In addition, the HAM/QUAD 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, because 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).

Because of the unique characteristics of noncontact ACL injury in elite ski racers, the risk for ACL injury/reinjury, the importance of HAM and QUAD 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 HAM and QUAD 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, HAM strength, and QUAD strength, both compared with the contralateral limb and with the limb average of uninjured elite skiers (control group). In addition, in uninjured individuals, we expected female skiers to demonstrate reduced thigh muscle strength compared with that in male skiers and no signs of bilateral limb strength deficits in both genders.

METHODS

Subjects. 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. Because of 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. In addition, five of the eight ACL-R ski racers experienced an injury on the nondominant 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 reports from nonelite ski populations and included meniscus injury, medial collateral ligament injury, and subchondral bone bruising (12,25). Subject characteristics (mean ± 1 SD) 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 a written informed consent to participate in this study.

TABLE 1. Subject characteristics.

	ACL-R Subjects				Control Subjects			
Characteristics	Female		Male		Female		Male	
n	5		3		8		13	
Age (yr)	24.2	±3.2	28.3	±0.6	20.9	±2.4	21.6	±3.4
Mass (kg)	69.4	±4.1	89.0	±9.3	64.8	±6.2	84.1	±7.3
Left limb mass (g)	9273.8	±772.4	12,606.9	±1555.4	9043.2	±1048.1	12,191.5	±1322.3
Right limb mass (g)	9593.4	±1168.9	12,677.1	±1122.0	9257.2	±1014.5	12,475.6	±1351.6
% body fat	20.5	±3.3	13.9	±3.0	16.4	±1.7	12.7	±2.2
Postoperation (months)	28.4	±13.5	19.3	±1.2	NA		NA	

NA, not applicable.

Test procedures. Testing was undertaken as part of a routine annual preseason fitness assessment, and all subjects were familiarized with the testing procedures. However, we were not able to obtain preinjury testing data. After completing the informed consent, subjects were given a standardized 10-min 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° of flexion (0° was defined as full extension).

With the arms across the chest, subjects performed three MVCs of isometric knee extension and knee flexion for both the right and left limbs (38). A short 30-s rest interval separated each repetition, and a 60-s rest interval separated each of the contraction types. Subjects were instructed to perform the contractions as quickly and forcefully as possible and to maintain the contraction for 2 s. Visual feedback was provided online 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 analog-to-digital converter (Windaq Data Acquisition Software version 2.78; DATAQ Instruments) and stored on an IBM personal computer. Data were then exported into a custom-built software program for analysis (MATLAB version R2013a).

Data analysis. Raw torque signals (V) were low-pass filtered using a fourth-order zero-lag Butterworth filter (2). The raw voltage data were converted to torque (N·m) 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 4% of the MVC. Contractile RTD was obtained as the mean slope of the torque versus time curve (i.e., Δtorque/Δtime (N·m·s^{-1})) over four distinct periods (i.e., 0–50, 0–100, 0–150, and 0–200 ms). RTD values calculated between the time intervals of 0–50 (RTD_{50}) and 0–100 ms (RTD_{100}) were used to assess the initial RTD, and RTD values calculated between the intervals of 0–150 (RTD_{150}) and 0–200 ms (RTD_{200}) were used to measure late RTD (4,31). The H/Q ratio was then calculated for the MVC and RTD, as follows (38):

$$\text{MVC H/Q ratio} = \text{HAM MVC/QUAD MVC}$$

$$\text{RTD H/Q ratio} = \text{RTD HAM/RTD QUAD}$$

MVC and RTD values were normalized to body mass for group comparisons (15). In addition, a limb average was calculated for the uninjured skiers and compared separately with 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. Thigh lean mass and body fat percentage were determined by dual-energy x-ray absorptiometry (DXA) scans according to the manufacturer's instructions (Discovery A QDR, software version 12.6.2; Hologic, Inc., Waltham, MA). 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 center 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 to capture all tissues in each of the lower limbs. A single experienced technician performed the data collection and analysis for all DXA scans.

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% for our primary outcome measures ($\beta = 0.80$). Because 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 an injury on the same leg, paired *t*-tests were used to assess within-group differences and a one-way ANOVA was used for between-group comparisons. For between-group comparisons, the body mass-normalized limb average for the control group was compared with each limb of the ACL-R skiers and the body mass-normalized limb average was also used to compare the 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. Nontransformed data are shown, and all data are presented as the mean value ± 1 SD, unless stated otherwise. Statistical significance was set at $\alpha = 0.05$.

RESULTS

Bilateral limb strength comparisons. 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. ACL-R skiers demonstrated significant deficits in HAM and QUAD maximal strength (i.e., MVC) and late RTD (i.e., RTD_{200} and RTD_{150}) in the ACL-R limb compared with the unaffected limb ($P < 0.05$) (Table 2). As expected, uninjured female skiers did not display significant bilateral limb differences across any of the HAM and QUAD strength variables. Although uninjured male skiers did not

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TABLE 2. A comparison of body weight-normalized HAM and QUAD strength between uninjured male and uninjured female skiers (limb average) and the ACL-R limb and unaffected limb of ACL-R ski racers.

Status	Sex	Limb	Movement	MVC ($N \cdot m \cdot kg^{-1}$)		RTD_{200} ($N \cdot m \cdot s^{-1} \cdot kg^{-1}$)		RTD_{150} ($N \cdot m \cdot s^{-1} \cdot kg^{-1}$)		RTD_{100} ($N \cdot m \cdot s^{-1} \cdot kg^{-1}$)		RTD_{50} ($N \cdot m \cdot s^{-1} \cdot kg^{-1}$)	
ACL-R	NA	ACL-R	Extension	3.44	±0.63*	13.40	±3.43*	15.66	±4.23*	18.20	±5.08	21.33	±5.62
			Flexion	1.52	±0.40*	6.30	±1.41*	7.58	±1.60*	9.55	±2.19	12.02	±1.86
		Unaffected	Extension	4.43	±0.98	17.32	±3.83	20.02	±4.66	22.89	±5.47	26.66	±8.68
			Flexion	1.78	±0.42	7.20	±1.88	8.73	±2.42	10.74	±3.13	13.25	±4.52
Control	Female	Average	Extension	3.96	±0.45	16.25	±0.87	18.91	±1.14	21.51	±1.27	24.26	±2.69
			Flexion	1.66	±0.22	6.83	±0.96	8.30	±1.17	10.35	±1.55	13.49	±2.97
	Male	Average	Extension	4.17	±0.56	15.95	±2.45	18.85	±2.59	22.52	±3.10	26.09	±3.89
			Flexion	1.86	±0.24	7.34	±0.79	8.71	±0.93	10.52	±1.07	11.63	±1.36

*Denotes a significant within-group difference ($P < 0.05$).
NA, not applicable.

have a significant bilateral limb difference in QUAD strength measures, there was a 5% bilateral limb difference in HAM maximal strength (MVC_{right}, 1.91 ± 0.25 $N \cdot m \cdot kg^{-1}$; MVC_{left}, 1.80 ± 0.24 $N \cdot m \cdot kg^{-1}$; $P < 0.05$) and an 8% difference in HAM late RTD ($RTD_{150\ right}$, 9.07 ± 0.99 $N \cdot m \cdot s^{-1} \cdot kg^{-1}$; $RTD_{150\ left}$, 8.35 ± 1.07 $N \cdot m \cdot s^{-1} \cdot kg^{-1}$; $P < 0.05$).

Comparison of limb strength for uninjured males and uninjured females. In contrast with our hypothesis, there were no significant differences between uninjured males and uninjured females in maximal QUAD or HAM strength (extension MVC: females, 3.96 ± 0.45 $N \cdot m \cdot kg^{-1}$; males, 4.17 ± 0.59 $N \cdot m \cdot kg^{-1}$) (flexion MVC: females, 1.66 ± 0.24 $N \cdot m \cdot kg^{-1}$; males, 1.86 ± 0.25 $N \cdot m \cdot kg^{-1}$) and no differences in initial RTD or late RTD (Fig. 1A). When normalized to the MVC, the uninjured female skiers demonstrated significantly greater HAM relative RTD_{50} ($P < 0.01$) and relative RTD_{100} ($P < 0.05$) compared with those in the uninjured males (Fig. 1B).

Comparison of limb strength for ACL-R group and uninjured group. Consistent with our hypothesis, the ACL-R limb demonstrated significant deficits in HAM and QUAD muscle maximal strength compared with the limb average for the uninjured skiers (extension MVC: ACL-R limb, 3.44 ± 0.63 $N \cdot m \cdot kg^{-1}$, vs uninjured, 4.09 ± 0.52 $N \cdot m \cdot kg^{-1}$; $P < 0.01$) (flexion MVC: ACL-R limb, 1.52 ± 0.40 $N \cdot m \cdot kg^{-1}$, vs uninjured, 1.78 ± 0.25 $N \cdot m \cdot kg^{-1}$; $P < 0.05$). Significant QUAD explosive strength deficits were also found in the ACL-R limb compared with the uninjured group ($P < 0.05$) (Fig. 2A).

No differences in HAM muscle explosive strength were observed in the ACL-R limb compared with the uninjured group. However, relative RTD_{50} (i.e., normalized to the MVC) was found to be higher in the ACL-R limb compared with that in the uninjured skiers (Fig. 2B) ($P < 0.05$). Figure 2C provides a comparison of the HAM 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. 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 $ratio_{50}$ ($P < 0.05$) (Fig. 3A). As the H/Q ratio can be elevated by diminished QUAD strength (i.e., smaller denominator), Figure 3B illustrates the HAM and QUAD RTD_{50} for each subject in the uninjured male and uninjured female groups

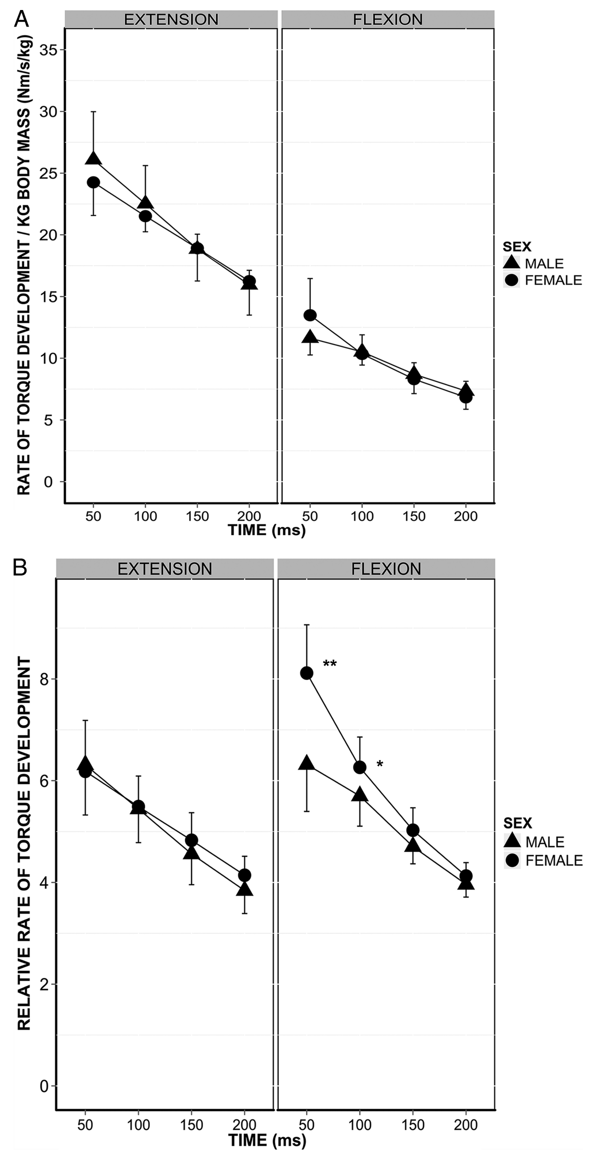

FIGURE 1—A. HAM and QUAD RTD for uninjured male and uninjured female ski racers. B. HAM and QUAD relative RTD (RTD/MVC) for uninjured male and uninjured female ski racers (*$P < 0.05$, **$P < 0.01$).

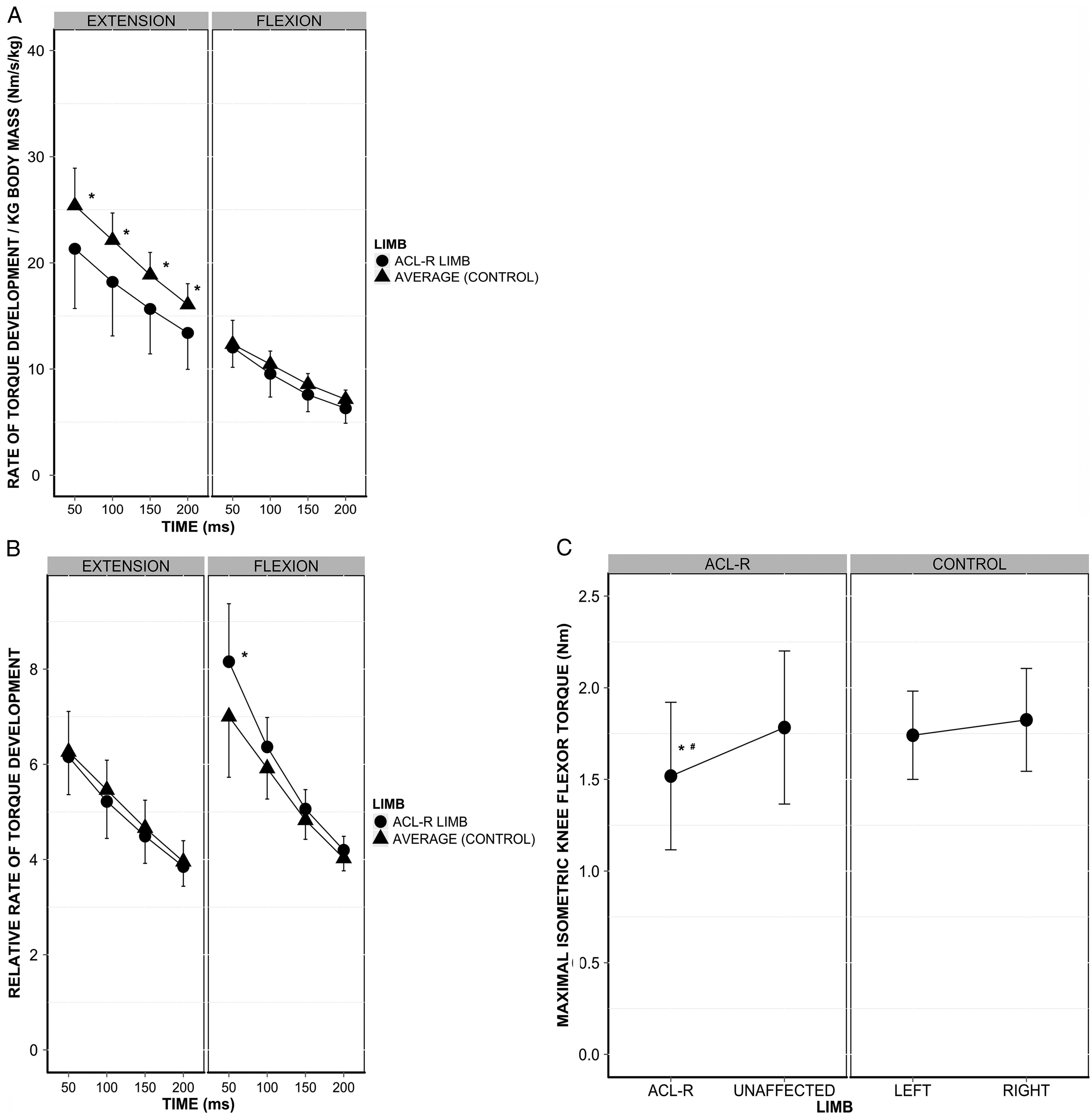

FIGURE 2—A. HAM and QUAD RTD for the affected limb of ACL-R skiers and limb average of controls (uninjured males and uninjured females). B. HAM and QUAD relative RTD (RTD/MVC) for the affected limb of ACL-R skiers and limb average of controls. C. Bilateral comparison of HAM MVC in ACL-R skiers and controls (*between-group difference, P < 0.05; #within-group difference, P < 0.05).

and is further stratified by subjects who demonstrated an H/Q ratio$_{50}$ of less than 0.4, between 0.4 and 0.5, and above 0.5. In addition, the plot is divided vertically by those with a bilateral asymmetry in QUAD 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 ratio$_{50}$ (>0.5) and a bilateral asymmetry in QUAD MVC greater than 10% (individual bilateral asymmetry, 11.1%). In addition, no significant differences were observed in bilateral QUAD strength for the uninjured females or in comparison with the QUAD strength of the uninjured males.

Comparison of H/Q ratios for ACL-R group and uninjured group. Contrary to our hypothesis, the ACL-R limb displayed an elevated H/Q ratio$_{50}$ compared with that in the uninjured group (P < 0.05) (Fig. 3C). Figure 3D illustrates the HAM and QUAD RTD$_{50}$ 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

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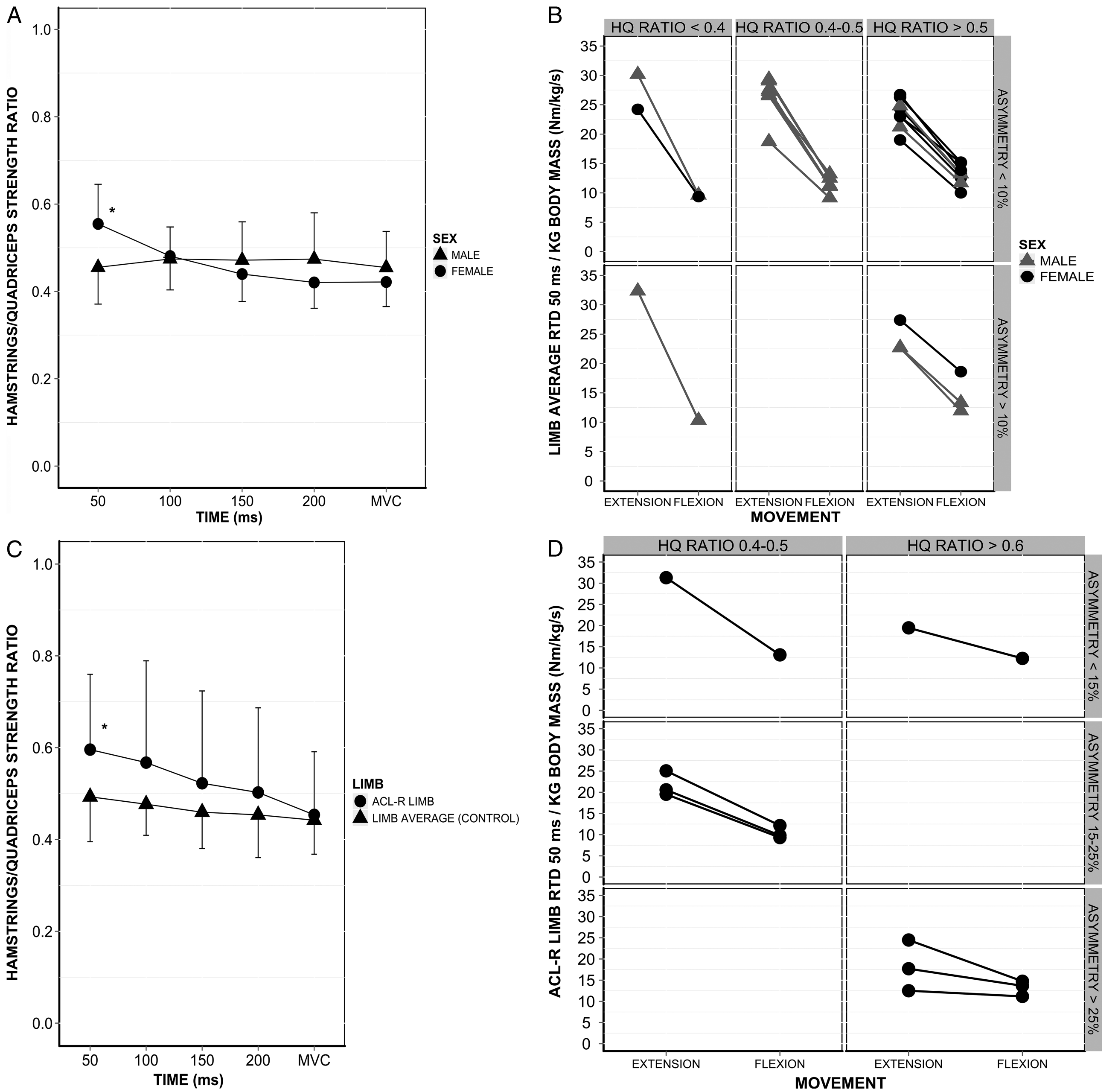

FIGURE 3—A. Ratio of HAM vs QUAD explosive strength (H/Q ratio) for uninjured male and female ski racers. B. Individual HAM and QUAD RTD at 50 ms (RTD_{50}) for male and female skiers, range in H/Q ratio, and asymmetry in QUAD MVC. C. H/Q RTD ratio for the affected limb of ACL-R skiers and limb average of control group skiers. D. Individual HAM and QUAD RTD_{50} for the ACL-R limb, range in H/Q ratio, and asymmetry in QUAD MVC (*P < 0.05).

ratio (>0.6). Because significant bilateral asymmetries were observed in QUAD maximal strength (MVC), the plot is divided vertically to show those subjects with a bilateral asymmetry in QUAD 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 $ratio_{50}$ (range, 0.60–0.89) along with the largest bilateral asymmetry in QUAD MVC reflecting deficits in the ACL-R limb. Furthermore, the ACL-R limb also demonstrated significant deficits in QUAD explosive strength and maximal strength compared with the contralateral limb and compared with the limb average of the uninjured group.

DISCUSSION

Comparison of limb strength for ACL-R skiers and uninjured skiers. To the authors' knowledge, the present study was the first to evaluate HAM and QUAD 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 reinjury 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 to develop appropriate guidelines for return to sport and strategies aimed at injury prevention (36).

The main findings of this study were the presence of significant deficits in QUAD maximal strength (MVC) and explosive strength (RTD) in the ACL-R limb of actively competing elite alpine ski racers compared with the contralateral limb and compared with the limb average of uninjured elite alpine ski racers despite long postoperative periods (mean, 25.0 ± 11.3 months). Because of the substantial risk for injury (11), the importance of QUAD muscle strength for ski performance (10,17,24), and the association between the restoration of QUAD strength and successful return to activity (6,26), the identification of QUAD strength deficits is highly relevant for the ACL-R elite alpine ski racer.

Our results are consistent with previous findings where long-term deficits in QUAD muscle strength have been identified in ACL-R subjects (14,15,21,26,35) and ACL-deficient knees (3,33). Although there is evidence showing that QUAD mass and strength are restored 18 months after surgery (19), some studies suggest a reduction in QUAD muscle voluntary activation (35) and peripheral muscle factors (21) as contributors to deficits in QUAD strength that are observed long after surgical reconstruction of the ACL. An investigation comparing QUAD strength of physically active ACL-R subjects more than 2 yr after surgery with that of physically active controls found a 25% strength deficit in the ACL-R limb when torque was normalized to body mass (14). Although 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 with the limb average of the control group. Furthermore, although Hiemstra et al. (15) did not make bilateral comparisons in the ACL-R group because of the possibility of contralateral limb deficits, the results of the present study found no difference in QUAD strength in the uninjured limb of the ACL-R skiers compared with the uninjured skiers.

We found significant bilateral limb deficits in QUAD maximal strength in the injured limbs compared with the uninjured limbs in the ACL-R skiers (mean asymmetry, 19%). The implications of significant bilateral asymmetry in QUAD maximal strength for ski performance and risk for ACL reinjury are unknown. However, uninjured ski racers display marked bilateral symmetry in QUAD strength (24) and are required to perform repeated bidirectional turns that involve large QUAD muscle loading (10,17). Consistent with Neumayr et al. (24), the mean bilateral asymmetry in QUAD maximal strength found for the uninjured skiers in the present study was less than 2%. This result suggests the importance of bilateral QUAD strength symmetry for ski racers and the importance of restoring QUAD strength after ACL-R in elite ski racers. In addition, because these deficits were found in actively competing ski racers, it also provides a rationale for long-term monitoring of QUAD strength after ACL-R in this population.

Because ski racers regularly perform resistance training exercises to prepare for competition, the large bilateral asymmetry in QUAD maximal strength may also be related to the exceptionally high torque values observed in the uninjured limbs (extensor MVC: males, 417.8 ± 17.3 N·m; females, 291.7 ± 57.7 N·m), which are considerably higher than the torque values 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 use of unilateral lower body movements, to address strength deficits in the ACL-R limb.

Although the restoration of QUAD strength is associated with a successful return to activity in ACL-R nonskiers (6,26), this has not been demonstrated in ACL-R elite ski racers. 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 QUAD maximal strength (36.9%). A second ACL-R athlete retired because of limitations from the knee injury one World Cup season after the study period. This particular subject had the largest asymmetry in QUAD maximal strength (54.2%). Although these examples are case related and hence do not provide strict scientific support for a causality between deficits in QUAD maximal strength and successful return to skiing after ACL-R, it suggests the potential relevance for future investigations into the relationship between QUAD strength deficits and a successful return to preinjury performance levels after ACL-R.

In addition to the bilateral deficits observed in QUAD maximal strength, significant bilateral deficits in QUAD explosive strength (RTD_{150} and RTD_{200}) were also found in the injured limb of ACL-R ski racers compared with their uninjured limb and compared with the limb average of the uninjured group. Because noncontact ACL injuries in ski racing occur in time frames less than 200 ms (8) and the reloading 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, because explosive strength and maximal strength are distinct abilities and are trained with different forms of resistance training exercise (2,4,37) the identification of specific QUAD strength deficits may be important for the ACL-R elite alpine ski racer to attain preinjury performance levels.

Although no bilateral limb differences were observed in the early phase of QUAD torque development (RTD_{50} and

APPLIED SCIENCES

RTD_{100}), the ACL-R limb still demonstrated lower values than those in 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, and to the pattern of initial motor neuron firing frequency (4). Because of the short time frame for noncontact 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 QUAD 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 reinjury in elite alpine ski racers.

The injured limb of the ACL-R ski racers also displayed significantly lower HAM maximal strength compared with that in the uninjured group and bilateral limb deficits in HAM maximal strength and late-phase explosive strength compared with the uninjured limb. Although there is an isolated report of a full restoration in HAM strength after semitendinosus autograft reconstruction (20), deficits in HAM strength have been observed in ACL-R subjects with semitendinosus autografts compared with uninjured controls (15) and compared with preoperative levels 2 yr after ACL-R (14). In addition, 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 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 HAM muscle strength observed in this group of ACL-R ski racers.

Nevertheless, the HAM 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). In addition, the HAM and QUAD muscles act in a coordinative fashion for knee stabilization and ACL protection (3,7,23,30,31,39). A relationship between deficits in HAM 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 HAM strength deficits and the corresponding risk for ACL reinjury 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.

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 with that in 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 after 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 torque and no difference in RTD_{50} compared with those in the uninjured group. Because the lower MVC values reduced the magnitude of the denominator in the calculation of the relative RTD_{50} ratio, this result should not be interpreted as a difference in the initial-phase HAM explosive strength ability for the ACL-R skiers.

Comparison of limb strength for uninjured male skiers and uninjured female skiers. Noncontact ACL injury in elite alpine ski racing is unique in that no clear sex-related differences 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 QUAD loading and evidence of pronounced HAM/QUAD cocontraction in skiing (10,17), specific HAM and QUAD 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. Although male ski racers were reported to have greater absolute strength values than that in 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 HAM and QUAD strength were found when corrected for body mass, which has been found elsewhere (15).

However, the uninjured female skiers had a greater relative RTD over the initial phase of the isometric MVC (relative RTD_{50} and relative RTD_{100}) compared with that in the male skiers. As discussed previously, 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 HAM torque obtained during the MVC. However, no bilateral limb deficits were observed in HAM maximal strength (MVC) for the female ski racers or in comparison with the uninjured males. Therefore, the greater relative RTD_{50} and relative RTD_{100} ratio may provide evidence of a qualitative difference in explosive strength for the male and female skiers included in the present investigation. Because we did not include other variables that may affect relative RTD in our analysis, such as physiological factors or type of resistance training exercise used by the subjects (2,4), we are unable to explain this finding.

Unexpectedly, although no bilateral limb differences in thigh muscle strength were found for the female skiers, the uninjured male ski racers displayed reduced HAM maximal strength (MVC) and late-phase explosive strength (RTD_{150}) in the left compared with values found in the right leg. Although the mean deficit in HAM maximal strength was only 5.3%, this asymmetry was consistently biased on the male ski racers, reflecting systematic right limb dominance. Because of the importance of the HAM muscle in resisting anterior shear forces that load the ACL (7,23) and evidence of substantial HAM/QUAD cocontraction during ski turns (17), the presence of bilateral limb deficits in HAM strength may be of concern for elite ski racers. In addition, although a clear association between bilateral HAM strength deficits and ACL injury has not been made, HAM 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 HAM muscle strength and ACL injury, this finding warrants future studies into the relationship between HAM muscle strength deficits and ACL injury. It also suggests that regular HAM 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. 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 linking a diminished H/Q ratio with ACL injury rates in elite ski racers exists. 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. (24) found H/Q ratios for elite ski racers ranging from 0.57 to 0.60 for isokinetic dynamometry, which limits comparison with that in the present investigation because of the use of isometric dynamometry. In our study, explosive strength and maximal strength H/Q ratios ranged from 0.42 to 0.55 for the uninjured female skiers and from 0.45 to 0.47 for the uninjured male skiers.

Interestingly, the uninjured female ski racers demonstrated a higher H/Q $ratio_{50}$ compared with that in the male ski racers (0.55 vs 0.46, respectively). To interpret the H/Q ratio, it is important to consider absolute strength values because of the possibility of an artificially inflated ratio resulting from deficits in QUAD strength (i.e., reduced denominator) (40). In our *post hoc* analysis, we evaluated the individual H/Q ratios alongside bilateral limb asymmetry in QUAD maximal strength (MVC). Of all the females presenting with the highest H/Q ratios, only one had a bilateral asymmetry in QUAD strength greater than 10% (individual asymmetry, 11%), and the mean bilateral limb asymmetry in QUAD maximal strength for the remaining uninjured female skiers was 0.6%. Furthermore, the uninjured females did not present with bilateral limb deficits in QUAD muscle explosive strength. Thus, we feel that it is reasonable to conclude that there was no evidence of a reduction in QUAD strength that may have contributed to an elevated H/Q ratio.

Together with these observations, the elevated H/Q $ratio_{50}$ found in the uninjured female skiers may indicate a better HAM/QUAD muscle strength balance over the initial phase of torque rise in the isometric MVC. Although 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, because HAM strength is often identified by experts as an important factor in noncontact ACL injury prevention for ski racers (18,24,34), it is possible that an increased emphasis on HAM strength development in ski racers contributed to the differences between the present investigation and the study performed by Zebis et al. (38) in high-level female soccer players. Because we did not include information on the resistance training program used by the subjects, we are unable to explain this finding.

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. (16) 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 $ratio_{50}$ compared with that in the uninjured skiers. However, because of the persistence of chronic QUAD weakness in ACL-R subjects (3,14,15,26,33,35), this result was interpreted alongside individual H/Q ratios and absolute QUAD 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 QUAD 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 QUAD strength (40).

An elevated H/Q ratio resulting from diminished QUAD strength may indicate better HAM/QUAD strength balance. However, as discussed previously, QUAD strength deficits may be disadvantageous for elite alpine ski racers because of the bidirectional turns and large QUAD muscle loading. Furthermore, although 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 QUAD strength and also included two individuals who were unable to make a full return to ski racing. On the basis of the present results, we suggest that the H/Q ratio be interpreted with caution in ACL-R ski racers and alongside absolute HAM/QUAD strength values to obtain a comprehensive assessment of HAM and QUAD muscle strength.

CONCLUSIONS

In conclusion, we found substantial deficits in QUAD maximal strength and explosive strength in the affected limb of actively competing ACL-R elite alpine ski racers compared with the contralateral limb and compared with uninjured ski racers. Deficits in HAM 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 HAM maximal strength and late-phase explosive strength. An increased relative RTD over the early phase of rise in isometric torque was found in the uninjured female skiers compared with that in uninjured male ski racers, whereas no sex differences were observed in any of the other HAM or QUAD 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. In addition, because of the limitations in recruiting subjects, we were unable to control for the graft type used in the ACL-R.

Despite these limitations, we conclude that HAM and QUAD maximal strength and explosive strength are important determinants for evaluating ACL-R ski racers and uninjured ski racers and should be included as part of a comprehensive strength assessment in elite alpine ski racers. These evaluations should be undertaken over long postsurgical periods in ACL-R skiers and should be continued even after full return to ski racing. Because 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 after ACL loss. Finally, although representing case examples, failure to regain QUAD strength after 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 QUAD strength deficits and return to skiing outcome. In addition, future studies should also control for the graft types used in ACL-R and further examine the relationship between graft type, HAM strength loss, and outcome after ACL-R. The relationship between HAM and QUAD strength deficits and return to skiing outcome requires careful and systematic evaluation in ACL-R elite alpine ski racers to identify ski-specific strength thresholds that should be met after injury. It is hoped that in future longitudinal studies, these issues will be addressed and assessments between HAM and QUAD strength and ACL injury/reinjury in elite alpine ski racers will be made a part of a multifaceted approach to injury prevention, including other risk factors for noncontact ACL injury in ski racing.

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