Asymmetry and Thigh Muscle Coactivity in Fatigued Anterior Cruciate Ligament–Reconstructed Elite Skiers

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ABSTRACT

JORDAN, M. J., P. AAGAARD, and W. HERZOG. Asymmetry and Thigh Muscle Coactivity in Fatigued Anterior Cruciate Ligament-Reconstructed Elite Skiers. *Med. Sci. Sports Exerc.*, Vol. 49, No. 1, pp. 11–20, 2017. **Purpose**: The acute effects of fatigue on functional interlimb asymmetry and quadriceps/hamstring muscle activity levels, including preparatory coactivation during squat jump takeoff and landing, were evaluated in elite alpine ski racers with/without anterior cruciate ligament reconstruction (ACLR). **Methods**: Twenty-two elite ski racers (ACLR, n = 11; control, n = 11) performed an 80-s repeated squat jump test (jump test) on a dual force plate system with simultaneous EMG recordings in vastus lateralis, vastus medialis, semitendinosus, and biceps femoris. Asymmetry index (AI) and jump height of body center of mass (H_{BCM}) were calculated from the ground reaction force. The normalized EMG amplitudes were obtained at takeoff, at the 25-ms interval prelanding, and at postlanding for the ACLR limb (affected limb), contralateral limb, and limbs of the control subjects (control limb). **Results**: Jump height decreased with fatigue for both groups, and ACLR skiers demonstrated elevated AI in the late takeoff phase versus the early takeoff and landing phases ($P < 0.0001$). No fatigue-induced changes in AI were found. The affected limb of ACLR skiers showed lower normalized quadriceps EMG activity at takeoff, prelanding, and postlanding along with increased hamstring activity prelanding and postlanding compared with the contralateral limb and control limb ($P < 0.001$). The affected limb, contralateral limb, and control limb all demonstrated increased quadriceps and decreased hamstring activity with fatigue ($P < 0.001$). **Conclusions**: Functional AI values were not changed with fatigue, and the affected limb of ACLR skiers who successfully returned to sport demonstrated more hamstring dominant landings compared with the contralateral limb and uninjured control limbs. Skiers with/without ACLR demonstrated more quadriceps dominant landings with fatigue. **Key Words:** KNEE INJURY, ALPINE SKIING, HAMSTRING, QUADRICEPS, INJURY PREVENTION, RETURN TO SPORT

Anterior cruciate ligament (ACL) injury and reinjury occur frequently in elite alpine ski racers (9,33) presumably when injury risk stemming from acute fatigue is increased (8). There are several high-energy injury mechanisms associated with rapid rotational and shear loading of the knee (7). Despite having returned to sport, ACL reconstructed (ACLR) ski racers may continue to display elevated bilateral functional asymmetry and quadriceps/hamstring strength deficits in the affected (ACLR) limb (27,28). To address these concerns, a return to sport neuromuscular assessment was proposed to evaluate a ski-specific envelope of function and ensure that ACLR skiers are safely fitted to return to racing (26).

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The dynamic stabilization of the knee using active muscular restraints is thought to be important for ACL injury prevention (22,23,39). Of particular interest is the preparatory quadriceps/hamstring muscle activity that helps to stiffen the knee joint before dynamic loading events, such as landing from a jump (6,14,35,39,41), which is a common mechanism of ACL injury in ski racing (7). Preparatory muscle activity is crucial for injury prevention because of the short time course (<100 ms) of ACL injury (29), which limits the potential for feedback loops to protect the knee (16,24,38). Athletes exhibiting increased quadriceps muscle dominance in the pretouchdown phase of landing, or change in direction, may be at increased risk of ACL injury (39). Conversely, hamstring muscle cocontraction is important for reducing anterior shear forces in the knee (4,10,37).

Consistent with the findings in elite alpine skiing, fatigued athletes are at increased risk for injury (20). Fatigued athletes may display lower limb landing kinematics that is associated with increased ACL loading (30) and diminished hamstring activity (5). For example, female handball players had reduced preparatory hamstring activity before landing after a sport-specific fatigue protocol (41). Similarly, fatigued male elite handball players demonstrated reductions in vertical jump height, quadriceps/hamstring rapid force production, quadriceps/hamstring maximum voluntary contraction force, and quadriceps/hamstring maximum EMG amplitudes (35).

The effects of acute fatigue on functional asymmetry in ACLR athletes, including ski racers, have received little scientific attention. Yet there appears to be a differential response in functional asymmetry index (AI) values between fatigued ACLR and uninjured subjects (36). In previous studies, ski racers without ACLR were characterized by high levels of functional between-limb symmetry that is believed to be important for performance given the bidirectional high force turns in alpine ski racing (7,8,27). Thus, the relationship between fatigue and functional asymmetry in elite alpine ski racers with/without ACLR may prove important for sport performance and injury prevention alike.

After ACLR, neuromuscular testing is recommended to ensure injury-related deficits are satisfactorily restored before return to sport (23,25–27,31). Neuromuscular testing may include an assessment of quadriceps/hamstring muscle activity and functional asymmetry in propulsive and decelerating actions such as those found in the vertical jump (24,31). As fatigued elite ski racers are at higher risk for injury, it seems important that neuromuscular assessments are not only ski-specific but also are performed with rested and acutely fatigued athletes (25,31). This type of neuromuscular testing may assist in developing individualized exercise programs for ACL injury prevention and rehabilitation.

The purpose of this study was to assess the effects of acute neuromuscular fatigue on vertical jump performance, bilateral functional asymmetry, and quadriceps/hamstring muscle activity in elite alpine ski racers with/without ACLR. Fatigue was induced using an 80-s repeated squat jump protocol (jump test). We hypothesized that vertical jump performance decreases with fatigue for both groups, and that functional asymmetry over the jump test for the ACLR group athletes increases compared with that observed in the uninjured control group athletes. We also hypothesized diminished hamstring activity in the prelanding and landing phases with fatigue, and a reduced quadriceps activity in the ACLR limb compared with that measured in the contralateral limb.

METHODS

Subjects. On the basis of previous research and a power analysis (27), it was estimated that 18 skiers were required to achieve a statistical power of 80% for the primary outcome variables. Thus, 22 elite skiers competing at the international level were recruited from Canada's national alpine skiing and skier cross programs, including 11 actively competing ACLR skiers (females, n = 5: age = 23.6 ± 1.8 yr, mass = 61.0 ± 5.3 kg; males, n = 6: age = 26.5 ± 5.8 yr, mass = 84.4 ± 9.0 kg) and 11 matched controls with no history of ACL injury (females, n = 5: age = 21.8 ± 3.2 yr, mass = 63.7 ± 4.6 kg; males, n = 6: age = 23.3 ± 3.3 yr, mass = 84.7 ± 5.1 kg). Because of the small sample size, no sex-specific comparisons were made. The mean postoperative period for the ACLR group was 3.0 ± 2.8 yr. Controls were included if they were 18 yr or older and active competitors at the international level defined as participation in the Federation International de Ski World Cup circuit. Subjects were excluded if they had a lower body injury or lumbar spine injury that might impair vertical jump performance.

For the ACLR group, only actively competing athletes at the Federation International de Ski World Cup level with full medical clearance to compete, age 18 yr or older, more than 12 months postsurgery, and with a history of primary ACL injury were included in the study. Subjects were excluded if they had a lower body injury or lumbar spine injury that impaired vertical jump performance. Seven subjects had a torn left ACL and four had a torn right ACL. Seven subjects received a semitendinosus (ST) autograft, one subject received a bone–patellar tendon–bone autograft, and three subjects received a cadaver allograft. The associated injury pathology was consistent with the literature and included medial/lateral meniscal tears, subchondral bone bruising, and first/second degree sprains of the collateral ligaments (18,32). The Conjoint Research Ethics Board at the University of Calgary approved the experimental protocol and all subjects gave written informed consent to participate in this study.

Subject preparation. The study was undertaken during routine annual fitness testing in the precompetition period, and all subjects were familiarized with the testing protocol. Subjects performed a standardized 10-min warm-up on a cycle ergometer followed by a dynamic stretching routine for the lower limb musculature. The same researcher identified the vastus medialis, vastus lateralis (VL), biceps femoris, and ST muscles. The skin over these muscles was carefully shaved and cleaned using an isopropyl alcohol solution. Bipolar surface electrodes with a 2-cm interelectrode distance (Norotrode, Ag/AgCl electrodes) were applied to the skin in the middle part of the muscle bellies on both limbs according to the recommendations from SENIAM 8 (21). Skin impedance was assessed, and a value of 7 kΩ or greater resulted in the repreparation of the skin and the application of new electrodes. After electrode placement, the EMG preamplifiers were taped to the skin, and a wide piece of compliant medical bandage was carefully secured over the electrodes and amplifiers to reduce movement artifacts.

Test procedures. Subjects were placed in a custom-built isometric dynamometer (MARK IV, University of Alberta, Alberta, Canada) with the knee angle set to 70° of knee flexion. Subjects performed three maximal voluntary contractions (MVC) of isometric knee extension and flexion with 60 s rest between tests. After the isometric MVC, subjects were given a 6-min rest interval before starting the jump-test protocol. Before commencing the jump test, subjects stood on two adjacent and leveled force plates with each leg placed on a separate force plate (25,27) and descended to the squat jump start position set at 90° of knee flexion. The squat jump start position was marked using an adjustable rope that contacted the hips directly behind the subjects. The squat jump depth was carefully monitored and controlled throughout the jump test by a certified strength and conditioning expert who stood directly beside the testing station. In addition, a piece of tape was symmetrically placed on each of the two force plates measuring the natural hip-width stance of the subjects, and foot placement on the force plates was monitored and controlled throughout the jump test. Subjects were instructed to perform each jump maximally and were provided with loud verbal feedback throughout the test to ensure a maximal effort was given on each single jump.

Subjects descended to the squat jump start position with the hands placed firmly on the hips and held this position for 4 s. A metronome timer indicated the start of the test and was set to repeat every 4 s. After each maximal jump, subjects landed back in the squat jump start position and maintained this position until they were cued for the next jump by a strong verbal command from the tester. Subjects performed 20 maximal jumps over the 80-s jump-test protocol. The operational definition of fatigue used for this study was an exercise-induced decrease in lower limb muscle power, which was evaluated using vertical squat jump testing (17). The test protocol was conducted through pilot testing with elite skiers in which different combinations of jump repetitions and time intervals were tested so that the technical parameters of the protocol could be controlled and the intensity was deemed comparable to that of a typical training run in ski racing.

Data acquisition and signal processing. The eight surface EMG signals were recorded using a telemetric EMG receiver (Telemyo DDTS Desktop Receiver; Noraxon, Scottsdale, AZ). EMG signals were preamplified with an overall gain of 500, filtered with a first-order high-pass filter set at 10 Hz and low-pass filtered with a cutoff at 500 Hz. Each EMG channel had a common mode rejection ratio greater than 100 dB. The vertical ground reaction force (Fz) from the right and left limbs was measured using a dual force plate system (Accupower Force Platform; AMTI, Wattertown, MA) and were recorded synchronously with the EMG signals (MyoReserch Version 3.8, Noraxon) at a sampling frequency of 1500 Hz. The EMG force data from all testing were collected and stored on a personal desktop computer for subsequent offline analysis.

Data analysis. After data collection, the data were exported for further analysis using custom-built computer scripts (Matlab Version R2015a; Mathworks, Natick, MA). Before data analysis, the alignment of the force and EMG signals was verified. The raw Fz voltage signals for the right and left limbs were then converted to newtons using a calibration curve and analyzed according to procedures described elsewhere (27,35). The takeoff velocity (TOV) of the body center of mass (BCM) was obtained using the impulse-momentum relationship of the vertical ground reaction force from the start of the (stationary) jump (BCM velocity equals zero) to the instant of takeoff. Jump performance was quantified using TOV with vertical jumping height of BMC (H_{BCM}) calculated as $H_{BCM} = TOV^2/(2g)$, with $g = 9.81\ m{\cdot}s^{-2}$.

Functional interlimb asymmetry was calculated using the vertical ground reaction force impulse for both legs independently over three defined time intervals (25,27): early-phase, late-phase, and landing-phase interval. The early-phase asymmetry was calculated from the initiation of the jump (time = 0 s) to the midpoint of the jump (time = ½ of the total jump time). The late-phase asymmetry was calculated from the midpoint of the jump to the instant of takeoff (27). The landing-phase asymmetry was calculated between the time points of touchdown and restabilization (return of Fz to stable body mass level). To identify the time point of restabilization, the SD of Fz obtained from the start of the trial during quiet standing (quiet period) representing the subject's system weight was calculated. Restabilization was defined when the vertical ground reaction force variation reached a level that was twice the SD observed in the quiet period before jumping. This time point captured the entire landing phase without extending into the quiet period for the subsequent jump. The kinetic impulse AI was calculated using the following formulae (27):

AI control

$$AI = \frac{(\text{left limb impulse} - \text{right limb impulse})}{(\text{Maximum of left and right impulse})} \times 100$$

AI ACLR

$$AI = \frac{(\text{contralateral limb impulse} - \text{affected limb impulse})}{(\text{maximum of contralateral and affected limb impulse})} \times 100$$

The EMG signals were high-pass filtered (cutoff frequency = 10 Hz) using a Butterworth fourth-order zero-lag filter and smoothed using a point-by-point moving 50 ms symmetric root mean square (EMG rms) filter (1). The EMG rms for each muscle during the jump test was normalized to the maximal EMG rms amplitude obtained from the respective muscle during the isometric MVC. The maximal EMG rms amplitude was obtained for the ascent phase and landing phase of each jump. In addition, the EMG rms amplitude was obtained for a 50-ms window around the instant of takeoff (toe-off) and the 25-ms interval preceding touchdown (prelanding) (6,39,41). The time windows for the EMG amplitude analysis were chosen based on the short time course of the ascent and landing phases in the squat jump and the inclusion of a discrete time point at takeoff. The timeframe for the prelanding phase was chosen because of the reliability and relevance of short duration prelanding activation for detecting ACL injury risk in other athlete populations (6,39).

Outcome measures. To evaluate the acute effects of fatigue on functional asymmetry, the AI values were averaged over sets of five jumps (set 1 = jumps 1–5, set 2 = jumps 6–10, set 3 = jumps 11–15, and set 4 = jumps 16–20). The fatigued state (set 4) could be compared with the rested state (set 1). The effects of fatigue on jump performance were also compared by evaluating the H_{BCM} averaged over the final five jumps (set 4) with the averaged H_{BCM} obtained for the first five jumps.

Overall quadriceps muscle activity was quantified by taking an average of the VL and vastus medialis EMG rms amplitudes, and gross overall hamstring muscle activity was obtained by taking an average of the biceps femoris and ST EMG rms amplitudes. To evaluate quadriceps versus hamstring muscle activation dominance, the magnitude of differential quadriceps–hamstring muscle activity was measured by calculating the normalized quadriceps muscle activity minus the normalized hamstring muscle activity (Quad-Ham), as described in detail elsewhere (39,40). In addition, the magnitude of valgus-related differential thigh muscle activity was calculated as the difference in VL–ST EMG activity by taking the normalized VL muscle activity minus the normalized ST activity (39). Muscle activity outcome measures in the fatigued state (set 4) were compared with the baseline rested state measurements obtained from set 1.

Statistical analysis. Because of the correlated nature of the outcome measures, linear mixed effect models (R, Version 0.98.1102, lme4 package) were fit separately for the jump performance outcome and the AI values with fixed effects for the factors group, jump set (factor levels: set 1 and set 4) and jump phase (factor levels: early phase, late phase, and landing-phase), and random intercepts for the athlete. Linear mixed effect models were also fit for the quadriceps muscle activity, hamstring muscle activity, VL–ST difference, and the Quad-Ham difference for the jump phases of interest with fixed effects for the factors jump set and limb status (factor levels: affected limb, contralateral limb, control limb). For the muscle activity models, random intercepts were set for the athlete and the limb within an athlete. The normality of the model errors was assessed, and a sensitivity analysis was performed to evaluate the influence of outliers. *Post hoc* analysis for assessing the effects of jump set on muscle activity was performed using a contrast to compare the outcomes for set 4 against the baseline value (set 1). The control limb (left and right limbs of the controls) was compared with the contralateral limb and affected limb of the ACLR subjects. The contralateral limb and affected limb of the ACLR subjects were also compared. All *post hoc* comparisons were adjusted using the single-step method in the multcomp package (R, Version 0.98.1102). Statistical significance was set at $\alpha = 0.05$ using a two-tailed test design.

RESULTS

Jumping performance and functional asymmetry. Vertical jump performance declined across the jump test for both groups ($\chi^2 = 130.6$, $df = 3$, $P < 0.0001$), and there was no difference between groups ($P = 0.08$). When controlling for the group effects, the mean ± SE decrease in vertical jump height from set 1 to set 4 was 5.9 (0.3) cm ($P < 0.0001$). Further, there was no change in functional AI values with acute fatigue ($P = 0.76$). However, an interaction was found between the jump phase and the subject grouping ($\chi^2 = 41.0$, $df = 2$, $P < 0.0001$). No difference in the AI values over the three jump phases was found for the control group (Fig. 1, right panel). However, ACLR athletes displayed a systematic change in asymmetry in the late phase of the jump takeoff, which was reflected by reduced impulse in the

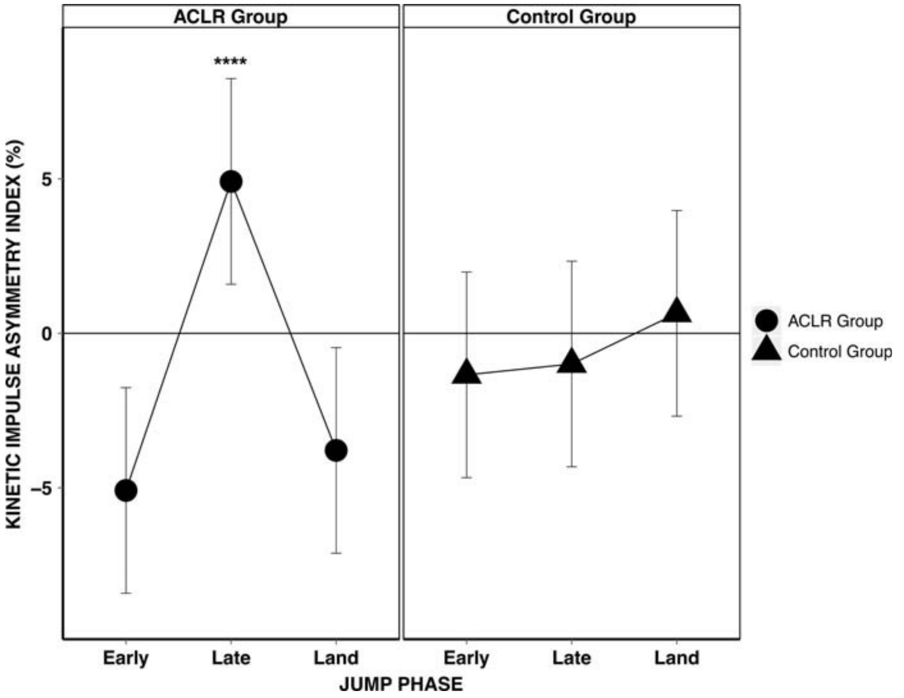

FIGURE 1—Mean functional AI values obtained in ACL reconstructed (ACLR) and noninjured (control) athletes. An interaction between jump phase and injury status (group allocation) was observed ($\chi^2 = 41.0$, $df = 2$, $P < 0.0001$). ACLR demonstrated systematically skewed asymmetry in the late takeoff phase of the squat jump (less vertical jumping impulse generated by the affected limb) compared with the early phase ($P < 0.0001$) and the landing phase ($P < 0.0001$). Data are shown as the mean AI ± 95% confidence interval. ****Significant difference from early-phase and late-phase asymmetry ($P < 0.0001$).

TABLE 1. Hamstring muscle activation (%MVC) across limbs (affected: ACLR limbs; contralateral: uninjured limb; control: uninjured controls) and jump sets for the ascent phase and at takeoff.

		Hamstring Activity Ascent Phase				Hamstring Activity at Takeoff			
				95% Confidence Interval				95% Confidence Interval	
Limb Status	Jump Set	Mean	SE	Lower	Upper	Mean	SE	Lower	Upper
Control	Set 1	0.354	0.041	0.274	0.434	0.245	0.027	0.193	0.298
	Set 2	0.327	0.041	0.247	0.407	0.212	0.027	0.160	0.265
	Set 3	0.321	0.041	0.241	0.402	0.204	0.027	0.152	0.256
	Set 4	0.304*	0.041	0.224	0.384	0.196*	0.027	0.143	0.248
Contralateral	Set 1	0.460	0.050	0.363	0.558	0.226	0.033	0.161	0.290
	Set 2	0.433	0.050	0.335	0.531	0.192	0.033	0.128	0.257
	Set 3	0.428	0.050	0.330	0.526	0.184	0.033	0.120	0.248
	Set 4	0.410*	0.050	0.312	0.508	0.176*	0.033	0.111	0.240
Affected	Set 1	0.496	0.050	0.398	0.594	0.260	0.033	0.196	0.325
	Set 2	0.469	0.050	0.371	0.566	0.227	0.033	0.163	0.291
	Set 3	0.463	0.050	0.365	0.561	0.219	0.033	0.155	0.283
	Set 4	0.446*	0.050	0.348	0.543	0.210*	0.033	0.146	0.275

Muscle activity is expressed as the EMG rms amplitude normalized to an isometric maximum voluntary contraction.
*Significantly different from set 1 ($P < 0.001$).

affected limb (ACLR) versus the contralateral limb ($P < 0.0001$) (Fig. 1, left panel).

Muscle activity squat jump ascent phase. No limb differences were found for the maximal hamstring muscle activity in the ascent phase ($P = 0.08$) or in the final takeoff phase ($P = 0.65$). However, there were main effects of fatigue on maximal hamstring muscle activity for the ascent and final takeoff phases (main effect of fatigue for ascent phase: $\chi^2 = 23.1$, $df = 3$, $P < 0.0001$; main effect of fatigue for final takeoff phase: $\chi^2 = 19.3$, $df = 3$, $P < 0.001$). Hamstring muscle activity decreased across all three limb conditions with fatigue (Table 1). No differences were found between limbs for the maximal quadriceps muscle activity levels in the ascent phase ($P = 0.24$), but there was a main effect of fatigue ($\chi^2 = 11.3$, $df = 3$, $P < 0.05$) (Table 2). At the final takeoff phase, there was a main effect of limb status on quadriceps activity with lower quadriceps activity in the affected limb compared with the contralateral limb ($\chi^2 = 7.6$, $df = 2$, $P < 0.05$) (Table 2). In addition, quadriceps muscle activity at takeoff declined with fatigue for all three limb conditions ($\chi^2 = 18.3$, $df = 3$, $P < 0.001$) (Table 2).

Muscle activity squat jump landing phase. No differences were found between limbs for maximal hamstring muscle activity in the landing phase ($P = 0.12$). However, there was a main effect of fatigue on hamstring activity ($\chi^2 = 29.6$, $df = 3$, $P < 0.0001$). Maximal hamstring muscle activity decreased with fatigue across all limb statuses in the final jump set (Table 3). The preparatory hamstring activity was greater in the affected limb of the ACLR subjects compared with the control limb in the prelanding phase ($P < 0.01$) (Table 3). Also, there was a main effect of fatigue on preparatory hamstring activity with a decrease observed for all limb conditions in the final jump set ($\chi^2 = 84.0$, $df = 3$, $P < 0.0001$) (Table 3). For the landing phase, there were no limb differences in the maximal quadriceps activity ($P = 0.54$), but there was a main effect of fatigue on quadriceps activity ($\chi^2 = 36.7$, $df = 3$, $P < 0.0001$). Landing-phase quadriceps activity increased significantly in the final set of the jump test for all limb conditions (Table 4). In addition, the preparatory quadriceps activity was lower in the affected limb compared with the contralateral limb of the ACLR group ($P < 0.01$). In an opposite direction to the hamstring activity, there was a main effect of fatigue on preparatory quadriceps activity with an increase observed for all limb conditions in the final set of the jump test ($\chi^2 = 28.6$, $df = 3$, $P < 0.0001$) (Table 4).

Preparatory quadriceps–hamstring coactivity. There was a main effect for limb status on the differential preparatory Quad-Ham muscle activity (quadriceps EMG minus

TABLE 2. Quadriceps muscle activation (%MVC) across limbs (affected: ACLR limbs; contralateral: uninjured limb; control: noninjured controls) and jump sets for the ascent phase and at takeoff.

		Quadriceps Activity Ascent Phase				Quadriceps Activity at Takeoff			
				95% Confidence Interval				95% Confidence Interval	
Limb Status	Jump Set	Mean	SE	Lower	Upper	Mean	SE	Lower	Upper
Control	Set 1	1.367	0.082	1.205	1.528	0.798	0.099	0.603	0.994
	Set 2	1.387	0.082	1.225	1.548	0.827	0.099	0.632	1.023
	Set 3	1.366	0.082	1.204	1.527	0.778	0.099	0.583	0.973
	Set 4	1.329	0.082	1.167	1.490	0.720*	0.099	0.524	0.915
Contralateral	Set 1	1.286	0.114	1.060	1.511	0.820	0.108	0.607	1.032
	Set 2	1.306	0.114	1.080	1.531	0.849	0.108	0.636	1.062
	Set 3	1.285	0.114	1.059	1.510	0.799	0.108	0.587	1.012
	Set 4	1.248	0.114	1.022	1.473	0.741*	0.108	0.529	0.954
Affected	Set 1	1.135	0.114	0.910	1.361	0.581**	0.108	0.369	0.794
	Set 2	1.156	0.114	0.930	1.381	0.610**	0.108	0.398	0.823
	Set 3	1.135	0.114	0.909	1.360	0.561**	0.108	0.348	0.773
	Set 4	1.098	0.114	0.872	1.323	0.503*,**	0.108	0.290	0.715

Muscle activity is expressed as the EMG rms amplitude normalized to an isometric maximum voluntary contraction.
*Significantly different from set 1 ($P < 0.01$).
**Significantly different from the contralateral limb ($P < 0.05$).

TABLE 3. Hamstring muscle activation (%MVC) in the landing-phase and prelanding activity levels across limb levels (affected: ACLR limbs; contralateral: uninjured limb; control: noninjured controls) and jump sets.

		Hamstring Activity Landing Phase				Hamstring Prelanding Activity			
				95% Confidence Interval				95% Confidence Interval	
Limb Status	Jump Set	Mean	SE	Lower	Upper	Mean	SE	Lower	Upper
Control	Set 1	0.282	0.027	0.229	0.335	0.143	0.017	0.109	0.178
	Set 2	0.254	0.027	0.200	0.307	0.118	0.017	0.084	0.153
	Set 3	0.248	0.027	0.195	0.301	0.106	0.017	0.072	0.140
	Set 4	0.219*	0.027	0.166	0.272	0.069*	0.017	0.035	0.103
Contralateral	Set 1	0.323	0.030	0.263	0.383	0.188	0.019	0.149	0.226
	Set 2	0.294	0.030	0.234	0.354	0.163	0.019	0.124	0.201
	Set 3	0.289	0.030	0.229	0.349	0.150	0.019	0.112	0.188
	Set 4	0.260*	0.030	0.200	0.320	0.113*	0.019	0.075	0.151
Affected	Set 1	0.358	0.030	0.298	0.418	0.217**	0.019	0.179	0.256
	Set 2	0.330	0.030	0.270	0.390	0.192**	0.019	0.154	0.231
	Set 3	0.324	0.030	0.264	0.384	0.180**	0.019	0.141	0.218
	Set 4	0.295*	0.030	0.235	0.355	0.143*,**	0.019	0.104	0.181

Muscle activity is expressed as the EMG rms amplitude normalized to an isometric maximum voluntary contraction.
*Significantly different from set 1 ($P < 0.001$).
**Significantly different from control limb ($P < 0.01$).

hamstring EMG) in the prelanding phase ($\chi^2 = 12.1$, $df = 2$, $P < 0.01$). Quad-Ham was lower in the affected limb compared with the other two limb conditions, reflecting more hamstring dominance and/or less quadriceps dominance in the ACLR limb (Fig. 2D). However, no limb differences were found in VL–ST coactivity difference (Fig. 2B). Finally, differential Quad-Ham muscle activity ($\chi^2 = 73.8$, $df = 3$, $P < 0.0001$) and differential VL–ST activity ($\chi^2 = 76.1$, $df = 3$, $P < 0.0001$) were elevated in the final set of the jump test irrespectively of limb status, reflecting increased preparatory quadriceps activity and decreased preparatory hamstring activity in response to fatigue (Figs. 2A and 2C).

DISCUSSION

We evaluated the acute effects of fatigue on functional interlimb asymmetry and quadriceps/hamstring muscle activity including preparatory (prelanding) coactivation during squat jump takeoff and landing in elite alpine ski racers with/without ACL reconstruction. It is important to undertake specific studies with elite ski racers because of the high prevalence of ACL injury (9), the unique injury mechanisms (7,8), and the high number of elite ski racers returning to competition post-ACL reconstruction (19).

Vertical jump performance and functional asymmetry. Fatigue was defined as an exercise induced impairment in muscle power evaluated by vertical jump height (17). Vertical jump height declined over the jump test for both groups. Contrary to our expectation, ACLR skiers did not display increased functional asymmetry with acute fatigue. This is in contrast to recent reports where ACLR males who returned to sport had reduced bilateral functional asymmetry with fatigue (36). The discrepancy between studies may be related to the testing methods. We characterized functional asymmetry over the entire takeoff and landing phases of the squat jump instead of a single time point (i.e., the instant of the peak vertical ground reaction force). The AI was calculated using the left and right limb impulses over discrete jump phases. This method has a high sensitivity for detecting deficits in ACLR skiers (27). The divergent results may also be caused by the longer postoperative period and the lower functional asymmetry for the ACLR skiers in this study compared with the subjects in the

TABLE 4. Quadriceps muscle activation (%MVC) in the landing-phase and quadriceps prelanding activity levels across limb levels (affected: ACLR limbs; contralateral: uninjured limb; control: noninjured controls) and jump sets.

		Quadriceps Activity Landing Phase				Quadriceps Prelanding Activity			
				95% Confidence Interval				95% Confidence Interval	
Limb Status	Jump Set	Mean	SE	Lower	Upper	Mean	SE	Lower	Upper
Control	Set 1	1.036	0.119	0.802	1.270	0.246	0.031	0.184	0.309
	Set 2	1.088	0.119	0.854	1.322	0.250	0.031	0.188	0.312
	Set 3	1.210	0.119	0.976	1.444	0.264	0.031	0.202	0.326
	Set 4	1.287*	0.119	1.053	1.521	0.318*	0.031	0.255	0.380
Contralateral	Set 1	1.041	0.150	0.744	1.337	0.272	0.035	0.203	0.341
	Set 2	1.151	0.150	0.855	1.448	0.275	0.035	0.207	0.344
	Set 3	1.129	0.150	0.832	1.425	0.289	0.035	0.221	0.358
	Set 4	1.188*	0.150	0.891	1.484	0.343*	0.035	0.274	0.412
Affected	Set 1	0.964	0.150	0.667	1.260	0.186**	0.035	0.118	0.255
	Set 2	0.890	0.150	0.593	1.186	0.189**	0.035	0.121	0.258
	Set 3	0.975	0.150	0.679	1.272	0.204**	0.035	0.135	0.272
	Set 4	1.068*	0.150	0.772	1.365	0.257*,**	0.035	0.189	0.326

Muscle activity is expressed as the EMG rms amplitude normalized to an isometric maximum voluntary contraction.
*Significantly different from set 1 ($P < 0.001$).
**Significantly different from contralateral limb ($P < 0.01$).

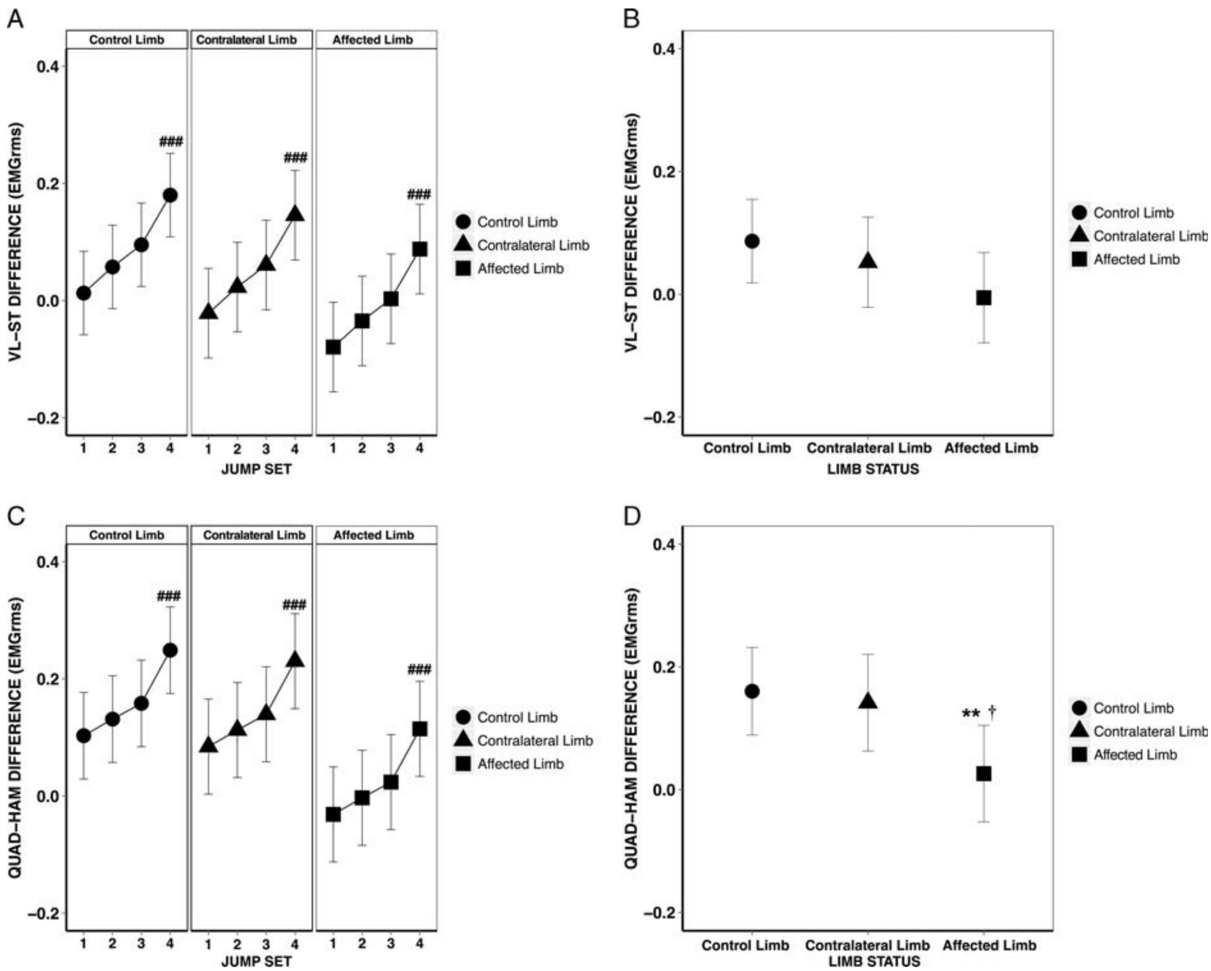

FIGURE 2—A comparison of the VL–ST difference (A, B) and the quadriceps–hamstring muscle activity difference (C, D) for the prelanding phase across jump sets and limb status. A main effect was found for fatigue (χ^2 = 73.8, *df* = 3, *P* < 0.0001) and limb status (χ^2 = 12.1, *df* = 2, *P* < 0.001) on the VL–ST difference. A main effect was also found for fatigue on the quadriceps–hamstring difference (χ^2 = 76.1, *df* = 3, *P* < 0.0001). Data are shown as the mean AI ± 95% confidence interval. ###Significantly different from set 1 (*P* < 0.001). **Significantly different from contralateral limb (*P* < 0.01). †Significantly different from control limb (*P* < 0.05).

Webster et al. (2015) study. Consistent with previous research, increased interlimb asymmetry reflecting deficits in the affected limb of the ACLR skiers were observed only in the late takeoff phase of the vertical squat jump (27). It was speculated that this may represent a neuromuscular adaptation resulting from the proximal to distal sequence of lower limb joint torque generation in the squat jump (11,27) and reduced knee extensor moments in ACLR limbs (3,13,14,36,38). The latter was potentially a result of reduced neuromuscular knee extensor activity at takeoff (present study) and/or from elevated levels of hamstring muscle coactivation reflecting an ACL protective motor strategy (3).

Maximal and preparatory muscle activity levels. The affected limb of the ACLR skiers displayed reduced quadriceps muscle activation at takeoff compared with the contralateral limb, which was consistent with an elevated functional AI for the late takeoff phase. Previous studies reported that tensile loading of the ACL was increased at small angles of knee flexion and with high levels of quadriceps muscle activation (10,13,38). Despite the observation of maximal quadriceps activation in jumping (4), it is possible that the reduced quadriceps activity at takeoff in the affected limb was a result of chronic knee joint instability after ACL repair (13,38).

All three limb conditions demonstrated quadriceps dominance for the prelanding phase with fatigue. Preparatory quadriceps muscle activity increased and hamstring muscle activity decreased resulting in a higher quadriceps–hamstring and VL–ST coactivity difference. The magnitude of differential VL–ST or valgus-related preparatory muscle activity recorded before touchdown in a side cut maneuver has been thought to be a predictor of ACL injury in female athletes (39). It was speculated that increased dominance of the lateral quadriceps relative to the medial hamstring muscles may reflect an impaired ability of preventing valgus knee collapse (39). Preparatory muscle activity was deemed important for ACL injury prevention because afferent mechanosensory feedback loops from the knee are too slow (>100 ms) to help stabilize the joint in case of high ACL loading (16,24,29,38). This observation was supported by studies highlighting the importance of quadriceps/hamstring coactivation for dynamic knee joint stabilization (2,4,10,37).

Despite the increased quadriceps dominance with fatigue, the ACLR limb showed reduced preparatory quadriceps activity and elevated preparatory hamstring activity compared with the other two limb conditions. As a result, preparatory quadriceps–hamstring coactivity before landing was systematically shifted toward increased hamstring dominance in the ACLR limb (cf. Fig. 2). There was no straightforward explanation for this finding. Our elite ACLR ski racers were high functioning and had made a full return to sport. In other settings, subjects who coped well with ACL deficiency demonstrated increased hamstring activity compared with noncopers (12,13), and ACL-deficient individuals had greater hamstring coactivation during maximal isolated knee extension compared with uninjured controls (3). In addition, athlete subjects presented with reduced hamstring activity compared with nonathletes, which was thought to be caused by an emphasis on forceful, dynamic knee extension training (4). In this case, regular hamstring strengthening exercise counteracted quadriceps dominance by increasing hamstring coactivity (4). Whether the increased preparatory hamstring activity in the affected limb was a result of preinjury training or postinjury rehabilitation cannot be determined with the current study design. Nevertheless, increased preparatory activity of the lower limb muscles, including the hamstrings (well known as ACL synergists), is an important determinant for the evaluation of successful return to sport after ACLR (23,31).

The present results were consistent with findings in the scientific literature that demonstrate acute reductions in hamstring muscle activity, hamstring strength, and hamstring reflex response after fatiguing exercise protocols (5,35,41). Zebis et al. (41) observed systematic postmatch decrements in hamstring muscle activity for female elite handball players in the prelanding and postlanding phases with no change in quadriceps muscle activity. This result paralleled acute reductions in hamstring and quadriceps MVC torque. They concluded that lower hamstring activity with fatigue might be a compensatory mechanism to maximize mechanical efficiency in the presence of quadriceps muscle fatigue.

Perhaps more critically, match-induced fatigue was reported to evoke marked acute impairments in quadriceps and hamstring rapid force production (35), which may be a critical element for return to sport after ACLR in elite ski racers (28). Biomechanical studies confirmed that impaired neuromuscular function of the hamstring muscles with acute fatigue resulted in increased tibial translation and elevated ACL strain in response to external anterior shear forces (5). The mechanisms of ACL injury in elite alpine ski racing involve high external shear forces in the knee (7), and injuries typically occur toward the end of a race, presumably when fatigue is present (8). In the present study, the shift toward quadriceps dominant preparatory and postlanding muscle activity in response to fatigue suggests that future research should be directed toward a better understanding of how quadriceps–hamstring coactivation may be involved in ACL injury for elite skiers.

Finally, ACLR skiers displayed less between-limb loading variation (i.e., demonstrated a more stereotypic loading pattern) compared with uninjured skiers who were highly symmetric across all jump phases. Notably, although the ACLR group loaded the ACLR limb to a lesser extent in the late takeoff phase, a greater impulse was generated by the ACLR limb in the early jump takeoff phase and landing-phase. The effects of returning to high-level ski racing with persistently elevated functional asymmetry remain unclear at this time. Given the high prevalence of knee osteoarthritis after ACLR (34), assessing interlimb loading variation with ACL injury and subsequent rehabilitation may be relevant for future research (15).

This study had limitations including the inability to control for the graft type and the inclusion of only high functioning ACLR elite alpine ski racers. Thus, this sample of ACLR skiers might not be representative of all ACLR elite skiers. In addition, because of limitations with recruiting subjects, we were unable to make a comparison between sexes, and we were not able to present preinjury data. To add clinical value to our results, prospective research aimed at further evaluating the relationship between functional asymmetry, quadriceps–hamstring muscle coactivity, and ACL injury/reinjury (23,24,39) is needed. Not only do ACLR elite alpine ski racers often make a successful return to competition (19), they may continue to display persistent functional deficits (27). In this context, increased emphasis on the development of sensitive neuromuscular tests for return to sport assessments is important to safeguard against injury/reinjury (22,23,26,27,31).

Fatigue is a complex process and no simple solutions for improving fatigue-resistance by means of injury prevention training have been found. However, it is important to identify neuromuscular deficits in ACLR and uninjured skiers that may be addressed through individualized training programs. The 80-s jump test used in the present study assessed functional outcome measures in both a rested and acutely fatigued state. Thus, the present research may provide the clinician and practitioner working with ACLR and uninjured ski racers with a useful and practical assessment tool to evaluate skiers across an envelope of function relevant to the demands of alpine ski racing.

CONCLUSION

In conclusion, signs of elevated and systematic between-limb asymmetry were observed in the late takeoff phase of the vertical squat jump in elite alpine ski racers with ACLR. However, no systematic changes in functional AI values were observed with acute fatigue. In addition, we observed decreased quadriceps muscle activity at jump takeoff in the ACLR limb compared with the contralateral limb, which was consistent with the finding of increased functional asymmetry in the late phase of the jump takeoff. All three limb conditions (i.e., ACLR limb, contralateral limb, and limbs of uninjured controls) became quadriceps dominant with fatigue (increased quadriceps activity concomitant with decreased hamstring activity) for the prelanding and landing phases of the squat jump. As this shift has been identified as a risk factor for ACL injury in other athlete populations, prospective research should evaluate its role in ACL injury/reinjury for elite ski racers. Finally, likely reflecting an ACL protective strategy, the ACLR limb demonstrated increased hamstring dominance compared with the contralateral limb and the limbs of uninjured elite alpine ski racers.

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