

Original article

A comparison of lower limb stiffness and mechanical muscle function in ACL-reconstructed, elite, and adolescent alpine ski racers/ski cross athletes

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Abstract

Purpose: The aim of this study was to compare mechanical muscle function in the eccentric/concentric phases of vertical bilateral jumping in anterior cruciate ligament-reconstructed (ACLR), elite (ELITE), and adolescent (ADOL) alpine ski racers and ski cross athletes.

Methods: Alpine ski racers/ski crossers (ACLR: $n = 12$, age = 26.7 ± 3.8 years; ELITE: $n = 12$, age = 23.9 ± 3.0 years; ADOL: $n = 12$, age = 17.8 ± 0.7 years; females: $n = 6$ per group, males: $n = 6$ per group) performed 5 maximal countermovement jumps (CMJs) and 5 squat jumps. The ground reaction forces for each limb were analyzed using dual force plate recording to obtain body center of mass (BCM) velocity, displacement, and power. The eccentric deceleration (ECC) and concentric phases were determined from BCM velocity. CMJ net concentric and ECC impulses were calculated (body mass normalized) along with the peak and mean BCM power and maximal vertical jump height. CMJ lower limb stiffness (LLS) was determined by the slope of the ground reaction forces vs. the BCM displacement curve over the ECC phase. Concentric and ECC asymmetry indices were calculated for each leg, and the left vs. right LLS was compared. Outcome measures (reported as mean \pm SD) calculated as a 5-jump mean were normalized to body mass and compared using an analysis of variance.

Results: No between-group differences were found for peak and mean power or jump heights. There were no group differences for LLS or net concentric phase impulse, but the net ECC impulse was lower in the ADOL group compared with ELITE skiers (ADOL: 1.33 ± 0.32 Ns/kg; ELITE: 1.59 ± 0.16 Ns/kg; $p < 0.05$). Although no group differences were found for ECC asymmetry indices, a group \times limb interaction was found for LLS ($p < 0.01$), which was systematically higher in the right vs. the left limb of ADOL skiers (right: 54.1 ± 17.9 N/m/kg; left: 48.7 ± 15.7 N/m/kg; $p < 0.01$).

Conclusion: ADOL skiers demonstrated decreased ECC impulse and systematic right limb dominance in LLS compared with ACLR and ELITE skiers. The implication of these findings for injury and performance are unknown, but further investigation into these potential relationships is warranted.

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Keywords: Between-limb asymmetry; Injury prevention; Knee injuries; Muscle power; Vertical jump

1. Introduction

Alpine ski racing is an extreme sport in which skiers achieve velocities in excess of 120 km/h while executing bidirectional turns that involve highly forceful coupled eccentric/concentric (stretch shortening cycle (SSC)) muscle actions.^{1,2} Skiers are known to be at high risk for lower limb injury, particularly to the

knee joint consequent to the strenuous physical demands and unpredictable environment of alpine ski racing.³ The most common knee injury is anterior cruciate ligament (ACL) rupture (ACL injury rate for males: 5.5 of 100 skiers per season; ACL injury rate for females: 5.4 of 100 skiers per season),⁴ and alpine skiers demonstrate a high prevalence of ACL reinjury after ACL reconstruction (ACL-reconstructed (ACLR) skiers).^{5–7} ACL injuries in alpine ski racers often involve trauma to other knee joint structures such as the menisci and articular cartilage, leading to early onset of joint degeneration.⁶

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The impact of ACL injury/reinjury on the health, safety, and performance of ski racers has led to recommendations for ACL injury prevention strategies focusing on the physical abilities of skiers.⁵ In female field/court-based athletes, lower limb biomechanical asymmetries,⁸ increased vertical jump landing forces,⁸ and hamstring/quadriceps strength deficits⁹ have been associated with ACL injury, suggesting a relevance for routine neuromuscular assessments to identify at-risk athletes.¹⁰ To date, only a single study has explored the relationship between physical fitness factors and ACL injury risk in alpine ski racers.¹¹ However, no associations were found between ACL injury prevalence, lower limb maximal strength, countermovement jump (CMJ) height, and the reactive strength index in the vertical drop jump performed on a single force plate.¹¹

Dual force plate systems that measure the vertical ground reaction force (F_z) from the left and right limbs simultaneously in the vertical jump may be helpful for detecting neuromuscular deficits related to ACL injury/reinjury, because this measure provides a direct comparison of between-limb mechanical muscle function and force (kinetic) asymmetries.^{8,12,13} Recently, an evaluation of between-limb kinetic asymmetry in the vertical CMJ and squat jump (SJ) recently was proposed for alpine ski racers using a dual force plate system.¹⁴ This experimental setup provides a practical and standardized test of functional asymmetry in coupled eccentric/concentric SSC muscle actions that are highly frequent in alpine ski racing. Additionally, mechanical muscle function and performance obtained through such CMJ and SJ analysis may provide deeper insight into neuromuscular function, sport-specific training adaptations, fatigue development, and neuromuscular recovery after ACL injury in alpine ski racers.^{13,15–19}

Neuromuscular screening can be considered particularly important for adolescent-aged alpine ski racers who may demonstrate a skewed left vs. right lower limb injury pattern accompanied by increased ACL injury prevalence in the final teenage years (overall ACL injury prevalence: 13%–15%; ACL injury prevalence in females: 22%; ACL injury prevalence in males: 9%).^{11,20} Here, novel parameters of mechanical muscle function obtained from CMJ force analysis, such as lower limb stiffness (LLS) and rate of force development (RFD), may help clinicians and practitioners to evaluate neuromuscular performance and identify neuromuscular deficits in young athletes that can be addressed through injury prevention training programs.^{17,21,22} Additionally, although eccentric/concentric kinetic asymmetries have been measured in skiers with ACLR, there are no studies to date examining limb stiffness in this population. Further, the unique demands of alpine ski racing, particularly the near maximal eccentric muscle actions,^{1,2} may lead to specific neuromuscular adaptations in elite skiers but less so in adolescent skiers, in turn providing less protection against injury in the latter athletes.²³ Mechanical muscle function testing may help to identify critical performance characteristics and neuromuscular adaptations that decrease injury risk in alpine skiers given this eccentrically demanding sport. However, this hypothesis remains to be tested.

The purpose of this study, therefore, was to compare the mechanical muscle function of ACLR, elite, and adolescent alpine ski racers during CMJ and SJ testing on a dual force plate system. It was hypothesized that elite alpine ski racers

would display greater eccentric deceleration impulse generation, greater LLS and higher mechanical muscle power output. Further, it was hypothesized that ACLR elite alpine ski racers would be characterized by more marked between-limb kinetic asymmetry, decreased limb stiffness in the affected (ACLR) limb, and diminished mechanical muscle power compared with elite alpine ski racers and adolescent skiers.

2. Methods

2.1. Study design

A total of 12 ACLR (world ranking = 32 ± 23 , mean \pm SD; skier cross athletes, $n = 3$), 12 elite (ELITE; world ranking = 37 ± 29 , mean \pm SD; skier cross athletes, $n = 1$), and 12 adolescent-level (ADOL; world ranking = 601 ± 756 , mean \pm SD) ($n = 6$ males per group; $n = 6$ females per group) actively competing alpine skiing and skier cross racers from the Canadian Alpine Ski Team were recruited during annual fitness testing sessions at the Canadian Sport Institute Calgary during the start of the off-snow training period (Table 1). The pattern of secondary injury associated with the primary ACL injury was consistent with reports from alpine skiing populations and included meniscus injury, medial collateral ligament injury, and articular cartilage injury (postoperative period of 4 ± 2 years, mean \pm SD).⁶ All subjects had medical clearance for ski training and race participation. Individuals in current treatment 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 their written informed consent to participate in the study.

2.2. Test procedures

Vertical CMJ and SJ testing was conducted as a part of routine testing.^{14,24} All skiers were highly familiar with the testing procedures and regularly performed maximal effort CMJs and SJs as a part of their off-snow training routines. Before testing, participants performed a standardized warm-up including 10 min on a cycle ergometer and light dynamic stretching for

Table 1
Subject characteristics (mean \pm SD).

Group	Body mass (kg)	Age (year)
ACLR		
Female	66.9 \pm 8.3	24.2 \pm 3.1
Male	90.0 \pm 7.9	29.2 \pm 2.7
ELITE		
Female	64.4 \pm 5.1	22.3 \pm 2.5
Male	83.7 \pm 4.9	25.5 \pm 2.7
ADOL		
Female	65.8 \pm 6.9	17.7 \pm 1.0
Male	79.5 \pm 8.5	18.0 \pm 0.0

Abbreviations: ACLR = anterior cruciate ligament reconstructed; ADOL = adolescent; ELITE = elite.

the lower body. Dynamic stretching targeted the muscles of the lower limbs (i.e., quadriceps, hamstrings, gluteal muscles, hip flexors, and plantar flexors) and included 10 repetitions it seems repetitive to include dynamic stretching again here with a 2 s hold in the stretched position.

Participants subsequently performed 5 maximal CMJs where they were instructed to descend rapidly to a self-determined depth and ascend maximally aiming for a maximal vertical jump height while keeping the hands firmly placed on the hips.¹⁴ The depth of the CMJ was not specified, allowing participants to use their preferred CMJ jumping strategy. After a 5 min rest interval, participants performed 5 maximal SJs.¹⁴ Participants were instructed to descend slowly to a knee joint angle of 90° knee flexion and remain stationary for 3 s. The knee angle was assessed/monitored by a qualified exercise specialist, and the jump start position was marked using an adjustable rope located behind the participant that was in contact with the gluteal fold. After achieving a stationary baseline force, a strong verbal cue was given to jump. Participants were instructed to jump maximally on each jump while keeping the hands firmly placed on the hips. For both the CMJ and SJ trials, jumps that deviated from the required technique were discarded and then repeated.

2.3. Force plate analysis

The vertical Fz from the right and left legs were measured simultaneously using a dual force plate system (Accupower Force Platform; AMTI, Watertown, MA, USA) at a sampling frequency of 1500 Hz and recorded on a personal computer (MyoReserch Version 3.8; Noraxon, Scottsdale, AZ, USA). Data were exported and analyzed using a custom-built computer program (Matlab R 2016a, Mathworks, Natwick, MA, USA) according to procedures described elsewhere.^{13–15,17,18}

2.3.1. CMJ and SJ mechanical muscle function

Briefly, the velocity of the body center of mass (BCM) was obtained by time integration of the instantaneous acceleration signal ((Fz/body mass) – 9.81 m/s²) calculated from the total Fz, summed from the right limb (Fz_{right}) and left limb (Fz_{left}). The CMJ jump phases were determined using the velocity of the BCM.¹⁵ The CMJ eccentric deceleration phase was defined as the time interval between the maximum downward negative velocity to the point of zero velocity achieved at the initiation of the ascent (deepest BCM position), whereas the CMJ concentric phase was defined from the starting point (zero BCM velocity) to the instant of jump takeoff. Mechanical muscle power exerted on the BCM was derived continuously throughout the jumping movement by calculating the instantaneous product of Fz and BCM velocity. The mean and peak mechanical muscle powers were determined for both the CMJ and the SJ as the average of the positive power curve throughout the concentric phase. Jump height was determined from the BCM vertical velocity at the instant of ground toe-off (jump height = takeoff velocity²/(2g)). The CMJ eccentric deceleration and concentric net impulses were calculated by time integration of Fz over selected time intervals (defined

elsewhere in this article) comprising the eccentric deceleration phase as well as the concentric phase of BCM excursion (as explained in detail elsewhere in this article). Additionally, Fz at peak power (FPP), BCM velocity at peak power (VPP), the maximum velocity of the BCM (V_{max}), and Fz at maximum velocity (FV_{max}) were obtained. Finally, SJ and CMJ contraction time in seconds was calculated, determined from the onset of the vertical takeoff (start of the jump) to the instant of ground toe-off. Outcome measures were normalized to body mass to allow between-group comparisons, and a 5-jump average was used from each participant for the overall statistical analysis.

2.3.2. LLS

First, the displacement of the BCM was calculated by time integration of the velocity of the BCM (double integration of the acceleration–time curve obtained from the Fz signal).^{17,22,25} The range of excursion (Δ BCM position) between the BCM position at the initiation of the eccentric deceleration phase (defined according to the time points obtained from the velocity of the BCM) and BCM position at the initiation of the concentric phase (ascent) corresponding to the deepest displacement of the BCM was determined. Total LLS (LLS_{total}) was calculated as the change in Fz (Δ Fz) through this range divided by the change in displacement (LLS_{total} = Δ Fz/ Δ BCM position), representing the ability to reverse the BCM downward acceleration through the displacement of the eccentric deceleration phase. In addition, LLS was calculated separately for each leg using Fz_{left} and Fz_{right} to obtain LLS for the right leg (LLS_{right} = Fz_{right}/ Δ BCM position) and left leg (LLS_{left} = Fz_{left}/ Δ BCM position), respectively. LLS_{total}, LLS_{left}, and LLS_{right} were normalized to body mass, and a 5-jump average was calculated for each participant and used in the overall statistical analysis.

2.3.3. Kinetic asymmetry index

The between-limb kinetic asymmetry index (AI) was calculated for discrete jump phases in the SJ and CMJ. For the CMJ, the total impulse was calculated by time integration of Fz over the eccentric deceleration phase and concentric phase, respectively.^{13,14} For the SJ, the early takeoff phase (initiation of the SJ to the peak of Fz in the concentric phase) and the late takeoff phase (peak Fz to the point of toe-off) were determined. Time integration of Fz over these discrete time intervals was performed to obtain the left and right leg total impulse. The 5-jump mean kinetic AI was calculated using the following formulas:¹⁴

AI non ACLR participants

$$= \left(\frac{\text{Left impulse} - \text{Right impulse}}{\text{Maximum of left and right impulse}} \right) \times 100\%$$

AI ACLR participants

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

2.3.4. Statistical analysis

All data were checked for normality (Shapiro-Wilk normality test) and homogeneity of variance (Bartlett test of homogeneity of variances) and were transformed when the assumption of a normal distribution was not met. However, nontransformed data are reported. For the jump performance outcome measures, a 3×2 analysis of variance was conducted with 3 levels for the between-subject grouping factor (group: ACLR, ELITE, and ADOL) and 2 levels for within-subject factor (jump type: SJ, CMJ). Group-wise comparisons of CMJ stiffness outcome measures, CMJ net eccentric impulse, CMJ net concentric impulse, and kinetic AIs were evaluated using analysis of variance with a within-group factor for the 2 levels of the limb to compare the right vs. left limb stiffness. Separate analyses of variance were conducted for each outcome measure. Owing to skewness of the data and unequal variances, nonparametric analysis (Kruskal-Wallis rank-sum test) was performed to compare the kinetic AI between the 3 groups. Pairwise comparisons were conducted using the Tukey adjustment. Cohen's f effect sizes were calculated with <0.2 considered trivial, ≥ 0.2 to <0.5 considered small, ≥ 0.5 to <0.8 considered moderate, and ≥ 0.8 considered large effect sizes. Statistical analysis was carried out using R (Version 1.0.153, Boston, MA, USA). All data are reported as the mean \pm SD unless otherwise stated. A statistical significance level of $\alpha = 0.05$ (2-tailed) was used.

3. Results

3.1. CMJ and SJ mechanical muscle function

No group differences were observed for mean mechanical power ($F(2, 33) = 1.16$, $p = 0.33$, Cohen's $f = 0.55$) or vertical jump height ($F(2, 33) = 1.21$, $p = 0.31$, Cohen's $f = 1.24$). However, CMJ mean mechanical power and vertical jump height were higher compared with the SJ (mean power: $F(1, 33) = 130.8$, $p < 0.01$, Cohen's $f = 1.99$; jump height: $F(1, 33) = 110.2$, $p < 0.01$, Cohen's $f = 1.83$) (Table 2). Although a group \times jump type interaction was found for peak mechanical power ($F(2, 33) = 3.45$, $p < 0.05$, Cohen's $f = 0.46$), pairwise comparisons revealed no differences between jump technique (Table 2). A group by jump type interaction was also found

for V_{\max} ($F(2, 33) = 3.93$, $p < 0.05$, Cohen's $f = 0.49$). CMJ V_{\max} was higher than SJ V_{\max} for ELITE ($p < 0.05$), whereas no difference was found for ADOL ($p = 0.05$) or ACLR ($p = 0.24$) skiers (Table 2). No group differences were found for FPP ($F(2, 33) = 1.52$, $p = 0.23$, Cohen's $f = 0.82$) or VPP ($F(2, 33) = 0.95$, $p = 0.40$, Cohen's $f = 1.00$). However, SJ FPP was higher than CMJ FPP ($F(1, 33) = 82.90$, $p < 0.01$, Cohen's $f = 1.58$) and SJ VPP was lower than CMJ VPP ($F(1, 33) = 183.1$, $p < 0.01$, Cohen's $f = 2.36$; Table 2).

Group differences were found for SJ contraction time ($F(2, 33) = 7.58$, $p < 0.01$, Cohen's $f = 0.68$) and CMJ contraction time ($F(2, 33) = 5.94$, $p < 0.01$, Cohen's $f = 0.60$). ADOL athletes displayed a slower SJ contraction time compared with ACLR and ELITE (ADOL = 0.60 ± 0.06 s, ACLR = 0.51 ± 0.07 s, ELITE = 0.53 ± 0.07 s; $p < 0.01$). Consistent with this finding, CMJ contraction time was also slower for ADOL skiers (ADOL = 0.96 ± 0.09 s, ACLR = 0.86 ± 0.05 s, ELITE = 0.87 ± 0.09 s; $p < 0.05$). Additionally, a group difference was found for the net eccentric deceleration impulse ($F(2, 33) = 3.75$, $p < 0.05$, Cohen's $f = 0.48$) with ADOL skiers presenting lower net eccentric deceleration impulse compared with ELITE skiers (Fig. 1).

3.2. LLS

No group differences were noted for LLS_{total} ($F(2, 33) = 0.93$, $p = 0.41$, Cohen's $f = 0.48$). However, a group by limb interaction was found for LLS_{left} vs. LLS_{right} ($F(2, 33) = 12.25$, $p < 0.01$, Cohen's $f = 0.86$). Although no between-limb differences in LLS were found for ELITE ($p = 0.46$) or ACLR ($p = 0.56$), ADOL skiers displayed systematically increased LLS_{right} compared with LLS_{left} (LLS_{right} = 54.1 ± 17.9 N/m/kg, LLS_{left} = 48.6 ± 15.7 N/m/kg; $p < 0.01$) (Fig. 2).

3.3. SJ and CMJ kinetic asymmetries

No between-group differences were found for AI calculated in the early SJ takeoff phase ($\chi^2 = 0.26$, $df = 2$, $p = 0.88$) or for AI calculated in the CMJ eccentric deceleration phase ($\chi^2 = 3.19$, $df = 2$, $p = 0.21$). However, between-group differences in AI were found for the SJ late takeoff phase ($\chi^2 = 12.9$, $df = 2$, $p < 0.01$) as well as for the CMJ concentric phase

Table 2
Comparison of SJ and CMJ mechanical muscle function measures between groups (mean \pm SD).

Group	Jump height (cm)	Relative peak power (W/kg)	Relative mean power (W/kg)	V_{\max} (m/s)	Relative force at max velocity (N/kg)	Relative force at peak power (N/kg)	Velocity at peak power (m/s)
ACLR							
CMJ	31.9 \pm 5.3	45.34 \pm 5.84	26.08 \pm 3.65	2.65 \pm 0.21	9.81 \pm 0.11	18.78 \pm 1.34	2.41 \pm 0.19
SJ	29.3 \pm 4.6**	46.39 \pm 6.19	21.77 \pm 2.71**	2.55 \pm 0.19	9.84 \pm 0.10	20.37 \pm 1.70**	2.27 \pm 0.16**
ELITE							
CMJ	35.8 \pm 4.7	49.19 \pm 4.65	28.46 \pm 2.42	2.79 \pm 0.17	9.80 \pm 0.07	19.38 \pm 0.74	2.53 \pm 0.17
SJ	31.7 \pm 4.2**	48.63 \pm 5.13	22.57 \pm 2.80**	2.63 \pm 0.16*	9.85 \pm 0.08	20.77 \pm 1.24**	2.34 \pm 0.16**
ADOL							
CMJ	34.2 \pm 6.8	49.61 \pm 7.32	27.24 \pm 5.25	2.74 \pm 0.24	9.77 \pm 0.04	19.84 \pm 1.63	2.49 \pm 0.22
SJ	29.4 \pm 4.8**	48.19 \pm 5.92	20.20 \pm 3.36**	2.55 \pm 0.19	9.80 \pm 0.04	21.13 \pm 1.31**	2.27 \pm 0.16**

* $p < 0.05$, ** $p < 0.01$ compared with CMJ.

Abbreviations: ACLR = anterior cruciate ligament reconstructed; ADOL = adolescent; CMJ = countermovement jump; ELITE = elite; SJ = squat jump; V_{\max} = max velocity of the body center of mass.

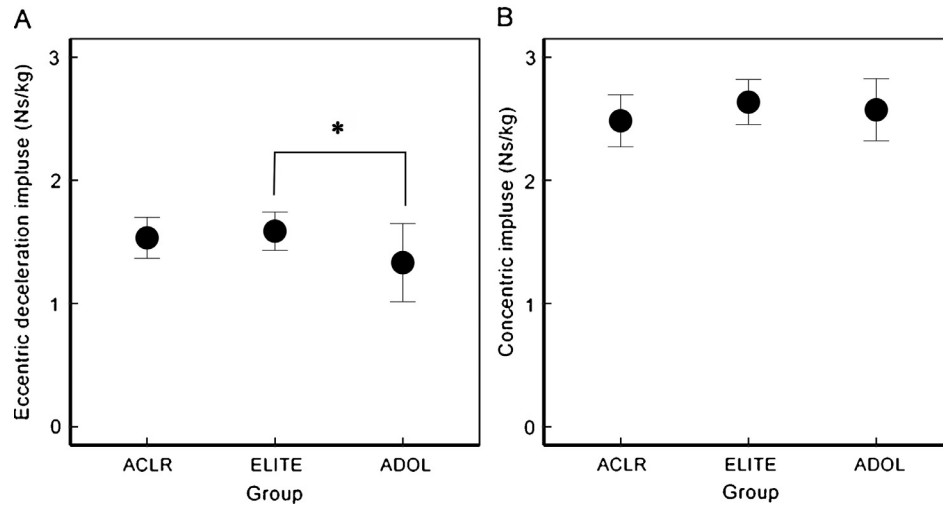


Fig. 1. Group comparisons of net eccentric deceleration impulse (A) and net concentric phase impulse (B). * $p < 0.05$. ACLR = anterior cruciate ligament reconstructed; ADOL = adolescent; ELITE = elite.

($\chi^2 = 8.62$, $df = 2$, $p < 0.05$). Increased CMJ concentric phase asymmetry and SJ late takeoff phase asymmetry were observed for ACLR skiers compared with ADOL and ELITE skiers (Fig. 3).

4. Discussion

The present study used a standardized and versatile vertical jump force asymmetry test to evaluate the mechanical muscle function of ACLR, elite, and adolescent alpine ski racers.¹⁴ This type of neuromuscular assessment may be relevant for

alpine ski racers given the high risk for lower body injury, especially to the ACL,³ and also given the potential for systematic neuromuscular testing to identify athletes at risk for sustaining noncontact ACL injury.¹⁰ In other athlete populations, hamstring vs. quadriceps strength deficits,⁹ lower limb biomechanical asymmetries,⁸ deficits in trunk control²⁶ increased vertical jump landing forces,⁸ and high knee abduction moments⁸ have previously been used to identify athletes at increased risk for ACL injury. Additionally, athletes with a history of previous ACL injury often suffer reinjury, and biomechanical variables related to muscle strength and power in rapid movements such as the vertical jump may help to identify such athletes at risk for recurrent ACL injury.^{12,27} Thus, routine biomechanical testing to identify neuromuscular deficits is recommended for athletes at risk for ACL injury/reinjury, including lower limb muscle strength/power, which includes the assessment of biomechanical lower limb asymmetries in ACLR athletes.^{9,28}

The primary finding of the present investigation was an increased impulse generation in the eccentric deceleration phase of the CMJ in elite vs. adolescent alpine ski racers. An explanation of this finding may be related to a sport-specific neuromuscular adaptation for elite alpine ski racers given the chronic exposure to high-force eccentric muscle loading during turns and landings.^{1,2,23,29} The effect of chronic eccentric loading from alpine skiing on the neuromuscular function of ski racers is currently unknown, but eccentric strength training in humans is known to stimulate muscular adaptations at molecular, muscle architectural, tendon, neural, and functional levels.^{30–32} Eccentric muscle actions are also characterized by unique neural control strategies compared with concentric and isometric actions, resulting in a decreased ability to maximally activate muscles and a decreased level of muscle activation for a given force level consequent to the intrinsic (passive) force capacity of muscle.^{33,34} Alternatively, the observed group differences in eccentric deceleration impulse generation in the CMJ may also be related to the specific jump strategy used by elite and adolescent racers, because jump strategy is known to

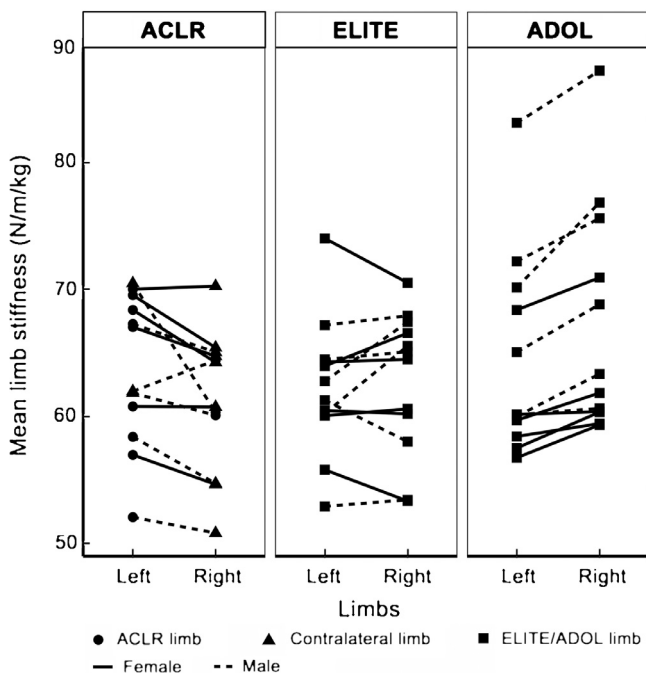


Fig. 2. Group comparison of right vs. left limb stiffness for ACLR, ELITE, and ADOL groups. Systematic limb stiffness asymmetry reflecting right limb dominance was found in the ADOL group ($p < 0.01$). ACLR = anterior cruciate ligament reconstructed; ADOL = adolescent; ELITE = elite.

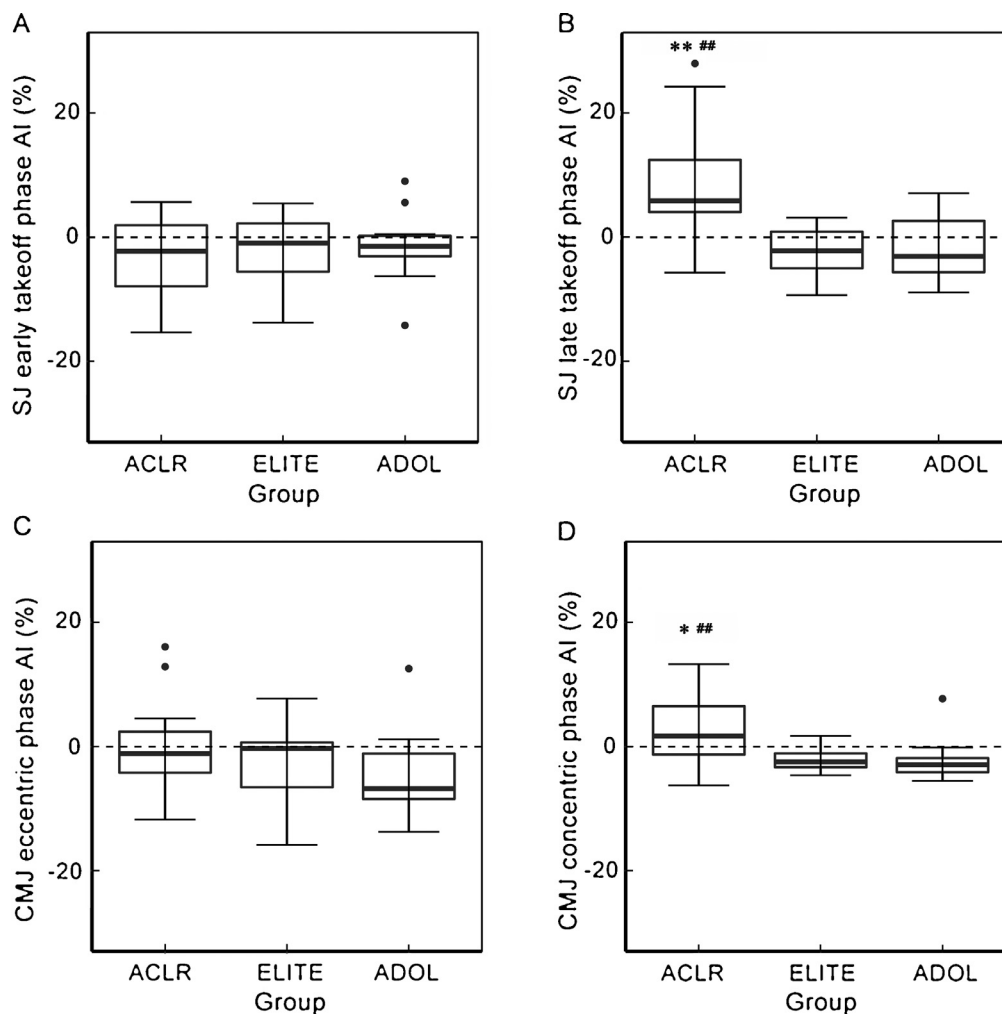


Fig. 3. Group comparisons of the SJ early takeoff phase AI (A), SJ late takeoff phase AI (B), CMJ eccentric deceleration phase AI(C), and CMJ concentric phase AI (D). * $p < 0.05$, ** $p < 0.01$ compared with ELITE; ## $p < 0.01$ compared with ADOL. ACLR = anterior cruciate ligament reconstructed; ADOL = adolescent; AI = asymmetry index; CMJ = countermovement jump; ELITE = elite SJ = squat jump.

influence force–time characteristics and performance of the vertical jump.³⁵ In the present study, the CMJ strategy was not controlled, allowing participants to choose their preferred jump technique. Thus, factors related to jump strategy should be considered alongside the potential for ski-specific neuromuscular adaptations in the interpretation of the present findings.

It is unclear how high RFD movements such as the CMJ relate to alpine ski racing performance given the preponderance of high-force, slow-velocity, eccentric/concentric muscle actions^{1,2} and the observation of ACL injury events that involve high-force, rapid eccentric loading of the lower limbs.³⁶ A case study report of the kinematics of an alpine skier who suffered an ACL rupture while skiing revealed a rapid increase in knee joint flexion (i.e., lengthening of the quadriceps muscle) occurring in an injury window of 228 ms. This timeframe and injury pattern are also consistent with details of ACL injury previously reported in elite alpine ski racers^{36,37} and are comparable with the duration of the CMJ eccentric deceleration phase reported in the present

investigation (eccentric deceleration phase duration = 174 ± 29 ms, mean \pm SD). However, the magnitude of loading in the eccentric deceleration phase of the CMJ is lower than the Fz_s found in typical alpine ski turns³⁸ and does not address other important neuromuscular capacities related to ACL injury such as quadriceps/hamstring coactivation.³⁹ Nevertheless, routine neuromuscular testing using movements such as the vertical jump may provide additional metrics for future studies aimed at understanding the relationship between modifiable physical factors, performance, and ACL injury in alpine ski racing.

In addition to displaying lower eccentric deceleration impulse compared with elite skiers, adolescent skiers displayed systematic right side dominance in LLS (Fig. 2). Although inconsistent with our initial study hypothesis, this finding nevertheless may represent an important observation given previous evidence of a limb bias for injury in young skiers.²⁰ A study including 456 adolescent alpine skiers found that the knee was the most commonly injured body part and that a higher number of lower limb injuries (63%) were

sustained on the left limb compared with the right limb (37%).²⁰ However, distribution of limb laterality (i.e., asymmetry) was not controlled at the study's outset.²⁰ Additionally, other limb dominance characteristics, such as the skilled limb, may be important for evaluating ACL injury risk in young athletes,⁴⁰ and the relationship between limb laterality and limb dominance in normal human movement remains unclear.⁴¹ The present study did not assess limb laterality or the preferred limb for skilled tasks such as kicking a ball. Thus, the finding of systematic right limb dominance in this group of adolescent skiers cannot be explained.

Modifiable risk factors for ACL injury in adolescent alpine ski racers have been identified previously and, although a reduced trunk flexion/extension strength ratio was associated with ACL injury, no relationship was found for bilateral CMJ mechanical power or maximal vertical jump height.¹¹ However, LLS assesses the ability to reverse the BCM downward acceleration through the eccentric deceleration phase of the CMJ, which is a critical determinant of CMJ performance.^{17,22,42,43} Further, because ACL injuries in ski racing involve substantial eccentric loading of the lower limbs,³⁶ biomechanical/performance analysis of the CMJ eccentric deceleration phase may provide further insight on neuromuscular deficits that can be addressed with ACL injury prevention training programs. Although the contribution of total vs. single limb stiffness to vertical jump performance has been assessed in adolescents²² and in elderly adults,²⁵ it has not been studied in the context of ACL injury prevention in alpine ski racers. Total (but not single) limb stiffness has previously been evaluated during SSC movement conditions after physical training programs,¹⁷ in acutely fatigued states,¹⁸ and in the differentiation of neuromuscular capacity in athletes with different sporting backgrounds.²¹ Finally, because alpine ski racing requires bidirectional turning,^{1,2} decreasing left-to-right lower limb asymmetries may be potentially important for ski racing performance, thus providing a potential rationale for future research incorporating CMJ limb stiffness asymmetry assessments as a component of routine neuromuscular screening protocols for alpine ski racers.

Despite the systematic right limb dominance observed for limb stiffness in adolescent skiers, no group differences could be detected for kinetic asymmetry (AI) in the CMJ eccentric deceleration phase. Consistent with previous reports, only ACLR skiers displayed elevated kinetic asymmetry indices in the CMJ concentric phase and the late takeoff phase of the SJ.¹⁴ These findings are aligned with other studies showing persistent bilateral asymmetry in vertical jumping and hop tests after ACLR.^{12–14,24,44} Contrary to our study hypotheses, no group differences were found in CMJ mechanical power and jump height, although CMJ performance exceeded SJ performance.

Adolescent skiers, however, demonstrated a slower jump contraction time compared with elite skiers, thus representing a slower jump strategy (i.e., diminished RFD capacity). The finding of greater mechanical power and higher jump height in countermovement vs. SJ has been observed elsewhere and may reflect increased muscle activity (elevated active state)

arising from the SSC occurring in the CMJ.^{35,42,43,45} Additionally, no group differences emerged for the force/velocity parameters, including the force/VPP, maximum takeoff velocity, or the magnitude of Fz force at maximum upward BCM velocity. Notably, these specific parameters have been suggested to characterize force vs. velocity dominant jumping strategies and have been used to evaluate the acute effects of fatigue on neuromuscular function.¹⁸ Monitoring CMJ performance through successive training cycles has also been used in other athlete populations to evaluate adaptation to training, detect overreaching, and evaluate neuromuscular fatigue.¹⁶ Based on the present results, SSC force/velocity mechanical muscle function did not seem to differ between elite, adolescent, and ACLR skiers. However, in addition to the potential value of CMJ and SJ force assessments to evaluate neuromuscular factors related to ACL injury, routine vertical jump monitoring may be helpful to evaluate neuromuscular fatigue. Further, standardized and practical assessments of neuromuscular fatigue seem warranted given the possible relationship between fatigue and injury in alpine ski racing.⁴⁶

The present comparison of mechanical leg muscle function of ACLR, elite, and adolescent alpine ski racers supports scientific efforts to identify the physiological and performance factors associated with alpine ski racing, which is important for on-snow performance and injury prevention.^{1,2,19,23,29} This study also introduced a new methodological approach for evaluating neuromuscular function in alpine ski racers, based on dual force plate analysis of CMJ and SJ performance. However, potential limitations of this study exist as well. First, studies on elite athletes are often challenged by small sample sizes, which affects the ability to make statistical comparisons. Given these challenges, the present investigation comprised both male and female skiers, and sex differences were not evaluated. This issue was accounted for by ensuring the same number of male and female participants in each group and further by performing body mass normalization of all outcome measures. This approach has been used previously with elite alpine ski racers to evaluate thigh muscle strength and RFD ability.⁴⁷ Second, the primary objective in the present investigation was to compare the mechanical muscle function of elite, adolescent, and ACLR alpine ski racers. Associations between mechanical muscle function and on-snow performance or injury were not examined, which would have required control over sex differences. Because this study was observational, it was impossible to link outcome measures to alpine ski racing performance or injury prevention. Furthermore, the study did not address questions around the time course change in these variables consequent to long-term participation in alpine ski racing. A fourth limitation is that the Fz asymmetries found in the vertical jump, more specifically the eccentric deceleration phase of the CMJ, may not be readily generalizable to injuries/performance in alpine ski racing given the complexity of alpine ski racing and the high external forces exerted in this sport. Nevertheless, this study provides sport scientists/sport medicine practitioners with a novel approach for evaluating the mechanical muscle function of alpine ski racers during SSC movements. Future experiments should be conducted to

verify if these differences exert an influence on ACL injury risk in this athlete population.

Assessing neuromuscular performance and function in alpine ski racers including the evaluation of between-limb kinetic (force) asymmetries in the vertical jump can provide coaches and sport science practitioners with specific and actionable information regarding trainable (modifiable) deficits that can be addressed through targeted off-snow physical training (e.g., strength training). Potential training interventions to address between-limb asymmetries may include the use of unilateral lower body strength training strategies along with biofeedback using a dual force plate methodology to help minimize between-limb differences. It is important to consider the time interval between surgery and neuromuscular testing for ACLR skiers. Appropriate post-surgical timing is important to permit sufficient tissue healing and the recovery of potential injuries associated with ACL tears, such as meniscal tears, chondral lesions, and graft donor sites for autograft ACL reconstruction procedures. These associated injuries occur frequently in alpine ski racers. In the present study, ACLR skiers were on average 4 years after surgery (range: 2–8 years) at the time of testing, which would have permitted sufficient tissue healing. Finally, although the present study did not make a comparison between sexes, sex differences in neuromuscular training and testing remain a critical perspective for enhancing performance and reducing lower body injuries, and should be considered by coaches and sport science practitioners in training program design and testing batteries.

5. Conclusion

The present assessment of lower limb mechanical muscle function of alpine ski racers by means of vertical jump force asymmetry testing revealed differences between elite, adolescent, and ACLR skiers. Notably, adolescent ski racers displayed lower eccentric deceleration impulse (time-integrated vertical Fz) compared with elite alpine racers, while also demonstrating systematic right-limb dominance in LLS during SSC (CMJ) testing. Consistent with previous reports, ACLR alpine ski racers seemed to be characterized by increased kinetic asymmetry in the concentric phase of the CMJ and the late takeoff phase of the SJ. Future research should continue to pursue practical neuromuscular assessments, such as vertical jump force asymmetry testing using a dual force plate methodology.^{13,14,24} This experimental approach can be used with alpine ski racers to monitor the effectiveness of off-snow physical training programs and in prospectively designed studies aimed at identifying modifiable (trainable) ACL injury risk factors.

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Authors' contributions

MJJ carried out the data collection, data analysis, statistical analysis, and manuscript preparation; WH participated in the study conception, study design, manuscript preparation, and manuscript editing; PA participated in the study conception, study design, manuscript preparation, and manuscript editing. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

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