Hamstring Muscle Activity After Primary Anterior Cruciate Ligament Reconstruction—A Protective Mechanism in Those Who Do Not Sustain a Secondary Injury? A Preliminary Study

Riann M. Palmieri-Smith, PhD, ATC, FNATA,*[†] Meagan Strickland, MA,[†] and Lindsey K. Lepley, PhD, ATC[‡]

Background: Individuals who experience a subsequent ipsilateral anterior cruciate ligament (ACL) reinjury may use hazardous muscle activation strategies after primary ACL reconstruction (ACLR). The purpose of this study was to compare electromyograms (EMGs) of the quadriceps, hamstrings, and gastrocnemius muscles during a dynamic hopping task among individuals with a single ACL injury (ACLx1), individuals who went on to have secondary ipsilateral ACL injury (ACLx2), and individuals who have never sustained an ACL injury (ACLx0).

Hypothesis: We expected that individuals who went on to experience a secondary ACL injury would use less quadriceps muscle activity as compared with individuals who experienced a single ACL injury.

Study Design: Cross-sectional study.

Level of Evidence: Level 3.

Methods: Fourteen individuals that were returned to play post-ACLR and 7 non-ACL-injured individuals participated. Individuals who had undergone an ACLR were placed into groups depending on whether they had experienced a secondary ipsilateral ACL reinjury postprimary ACLR. EMG data of the vastus lateralis, biceps femoris, and lateral gastrocnemius were measured during 2 phases of a single-leg dynamic hopping task: preactivity (100 ms prior to ground contact) and reactivity (250 ms post-ground contact). Processed EMG data were compared across groups using 1-way analyses of variance, with post hoc independent *t* tests where appropriate ($P \leq 0.05$).

Results: At preactivity, ACLx1 ($0.48\% \pm 0.2\%\text{max}$) was found to use significantly more hamstring activity than ACLx2 ($0.20\% \pm 0.1\%\text{max}$, $P = 0.018$), but not than ACLx0 ($0.38\% \pm 0.1\%\text{max}$, $P > 0.05$). At reactivity, both ACL groups were found to use less quadriceps activity than ACLx0 (ACLx1: $0.38\% \pm 0.1\%\text{max}$, $P = 0.016$; ACLx2: $0.40\% \pm 0.1\%\text{max}$, $P = 0.033$; ACLx0: $0.58\% \pm 0.1\%\text{max}$), but not than each other ($P > 0.05$).

Conclusion: Quadriceps muscle activity during landing was diminished in all ACL participants as compared with participants who had never sustained an ACL injury. Individuals who did not experience a secondary ipsilateral ACL reinjury (ACLx1) used greater levels of hamstring activity prior to landing.

Clinical Relevance: The higher hamstring activity in patients who did not experience a secondary injury may be interpreted as a protective mechanism that is used to dynamically stabilize the reconstructed limb.

Keywords: knee; thigh; muscle activity

From [†]School of Kinesiology, University of Michigan, Ann Arbor, Michigan, and [‡]Department of Kinesiology, University of Connecticut, Storrs, Connecticut

*Address correspondence to Riann M. Palmieri-Smith, PhD, ATC, Central Campus Recreation Building 4745G, 401 Washtenaw Avenue, Ann Arbor, MI 48197 (email: riannp@umich.edu).

The following authors declared potential conflicts of interest: Riann M. Palmieri-Smith, PhD, ATC, is an associate editor for *Sports Health*. Meagan Strickland, MA, reports the fact that a family member's data were included in the data set used in this article.

DOI: 10.1177/1941738119852630

© 2019 The Author(s)

Anterior cruciate ligament (ACL) injuries are increasingly common among active individuals. Each year, it is estimated that more than 200,000 ACL injuries occur in the United States alone, with 90% of the individuals who injure their ACL electing to undergo ACL reconstruction (ACLR).^{11,17} After primary ACLR, it is predicted that as many as 30% of reconstructed individuals will go on to sustain a secondary ipsilateral or contralateral ACL injury.¹⁴ Notably, the outcome of secondary ACLR is far less favorable as it leads to lower levels of self-reported function, impaired functional ability and can accelerate the progression of osteoarthritis.^{14,21,22,31} Given the poor outcomes associated with secondary ACL injury, it is imperative for researchers and clinicians to identify modifiable factors that can be improved postprimary ACLR to potentially prevent ACL reinjury.

Muscle activity is a modifiable factor that may contribute to the high rate of ACL reinjury.³ After primary ACLR, alterations in muscle activity commonly manifest in the quadriceps and hamstring muscles, with individuals demonstrating decreased quadriceps activity and increased hamstring activity in relation to their contralateral limb and when compared with healthy controls.³⁰ Importantly, these alterations in muscle activity are associated with biomechanical alterations that are thought to contribute to ACL reinjury.²⁰ Though these alterations in muscle activity have been well studied in primary ACLR individuals, the muscle activity of individuals who go on to experience a secondary ACL rupture has not been reported. Based on the available literature, it seems plausible that individuals that experience a subsequent ipsilateral ACL reinjury may display muscle activation strategies that are particularly hazardous when they are returned to play after their primary ACLR. Given that muscle activity can be improved through neuromuscular exercises, understanding the contributions of alterations in muscle activity to ACL reinjury is critical, as rehabilitation professionals can modify this outcome.

Thus, the primary purpose of this investigation was to compare muscle activity of the quadriceps, hamstrings, and gastrocnemius during a dynamic hopping task between individuals with a single ACL injury (ACLx1) and individuals who went on to have secondary ipsilateral ACL injury (ACLx2) at the time when individuals were cleared for return to play postprimary ACLR. A secondary purpose was to determine if ACLx1 and ACLx2 individuals differed from a group of healthy, control participants (ACLx0). We expected that individuals who went on to experience a secondary ipsilateral ACL injury would use less quadriceps muscle activity as compared with individuals that experienced a single ACL injury.²⁸ Furthermore, based on the previous literature,^{1,20} we anticipated that all ACL-reconstructed individuals would display reduced lower extremity muscle activity as compared with healthy controls.

METHODS

Study Design

A cross-sectional design was used in this study. Participants were tested on a single occasion where we measured

electromyograms (EMGs) recorded during a hopping task. Primary outcome variables included preactivity and reactivity EMG activity recorded from the vastus lateralis, biceps femoris, and lateral gastrocnemius.

Participants

Participants from the current study were part of a larger clinical study designed to examine the magnitude of quadriceps activation failure and strength that contributes to biomechanical asymmetry after ACLR.²⁵ ACL participants were eligible for enrollment into the parent study if they met the following criteria: (1) were between 14 and 30 years old, (2) were planning to undergo rehabilitation at our orthopaedic clinic, (3) had an acute ACL injury (defined as reporting to a physician within 48 hours postinjury), (4) had no previous history of surgery to either knee, (5) had not suffered a previous ACL injury, and/or (6) did not have a known heart condition. A total of 130 patients were enrolled in the parent study. We reexamined the medical records of all participants on completion of the parent investigation and found that 7 patients went on to reinjure their ACL graft and these seven patients were included in the ACLx2 group. Once the ACLx2 group was formed, we then went through the remaining ACL patients from the parent investigation and matched the ACLx2 patients with patients who only tore their ACL on a single occasion (ie, 1:1 matching between ACLx2 and ACLx1 groups). When matching ACLx1 patients with ACLx2 patients, we also considered gender (same gender), age (± 2 years), graft type (same graft type for primary ACLR), and preinjury activity level (eg, Tegner scale score⁵; same Tegner score). A small number of participants who never had torn an ACL were also recruited into the parent investigation (ACLx0) and were invited to participate if they had (1) no history of ACL injury or reconstruction, (2) no lower extremity injury in the past 6 months, and/or (3) no current pain in either knee joint. Pregnant females were excluded from both the noninjured and the ACL groups. Ten uninjured participants were available from the parent study and 7 were selected that were the closest matches to our patients in terms of gender (same gender), and age (± 3 years). Demographic data for all 3 groups can be found in Table 1. All ACL participants (ACLx1 and ACLx2) were followed for a minimum of 3 years post-ACLR. Informed consent was obtained from all participants and approved by the university's institutional review board.

Rehabilitation Program After ACLR

All ACLR participants completed a "standard" rehabilitation protocol at 1 orthopaedic outpatient clinic (see the Appendix, available in the online version of this article). The rehabilitation protocol emphasized full range of motion immediately and knee flexion as tolerated. Quadriceps reeducation and muscle strengthening (ie, quad sets, straight leg raises, neuromuscular electrical stimulation) were emphasized immediately postsurgery and progressed as tolerated to more dynamic strengthening throughout each patient's ACLR rehabilitation. In general, the

Table 1. Participant demographics (mean $\pm$ SD)

Group	Participants n = 7	Sex	Age, y	Height, cm	Mass, kg	BMI, kg/m ²	Time From ACL Injury to ACLR, d	Time to Test Post-ACLR, ^a d	Time From Test Post-ACLR to Secondary ACLR, ^b d	Graft Type	Tegner Score	Meniscal Status
ACLx0	n = 7	5m,2f	22.57 $\pm$ 3.3 ^c	176.78 $\pm$ 5.3	70.80 $\pm$ 6.0	22.66 $\pm$ 1.8	NA	NA	NA	NA	6.86 $\pm$ 1.95	NA
ACLx1	n = 7	5m,2f	17.14 $\pm$ 2.7	182.87 $\pm$ 6.0	72.77 $\pm$ 6.8	21.8 $\pm$ 2.27	83.71 $\pm$ 60.9	230.71 $\pm$ 50.5	NA	PT = 7	6.29 $\pm$ 1.89	Repair: 1 No injury: 5 Mensiscectomy: 1
ACLx2	n = 7	5m,2f	16.00 $\pm$ 1.1	177.44 $\pm$ 3.6	70.49 $\pm$ 6.5	22.3 $\pm$ 1.59	50.86 $\pm$ 18.5	189.71 $\pm$ 10.7	490.29 $\pm$ 430.9	PT = 7	6.14 $\pm$ 2.96	Repair: 0 No injury: 6 Mensiscectomy: 1

ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; ACLx0, no ACL injury group; ACLx1, single ACL injury group; ACLx2, double ACL injury group; BMI, body mass index; NA, not applicable; PT, patellar tendon.

^aTime to test post-ACLR is the time point when participants completed the hopping task for this investigation.

^bTime from test post-ACLR to secondary ACL injury is the time from study testing until the day they sustained a secondary ACL injury.

^cDifferent than the ACLx1 and ACLx2 groups.

rehabilitation protocol consisted of 2 appointments per week, beginning the first postoperative week, and concluding approximately 6 months post-ACL reconstruction.

Testing Procedures

To record muscle activity at time of return to play, the skin for each electrode site was shaved and cleaned with isopropyl alcohol. Surface EMG electrodes (DE-2.1, Delsys Inc) with a 10-mm interelectrode distance were then secured over the muscle bellies of the vastus lateralis, biceps femoris, and lateral gastrocnemius according to the technique described by Delagi et al.¹³ A single ground electrode was placed on the right patella. Raw EMG data were collected using a commercial EMG system (Bagnoli 16-Channel, Delsys Inc) that was sampled at 1200 Hz during dynamic activity.²⁶

To indicate ground contact, participants were instructed to land on a force plate (OR6-7; Advanced Medical Technology, Inc) sampling at 1200 Hz with their ACL-reconstructed limb (ACLx1 and ACLx2 groups) or their dominant limb (ACLx0 group). This resulted in all participants landing on their right leg (ie, ACLx1 and ACLx2 groups had torn their right ACL and all ACLx0 participants were right limb dominant). The distance to hop was determined by each participant's leg length, defined as the tip of the greater trochanter to the tip of the lateral malleolus.³³ Trials were collected until at least 3 successful trials were achieved on the reconstructed limb or right limbs in the case of ACLx0 participants. Successful trials were defined as trials in which participants landed on the force platform and were able to balance on their take-off limb without touching the floor with the contralateral limb. Participants were allotted a 1-minute break between trials and there was no limit on the number of trials a participant was allowed to perform, though all participants were able to complete 3 successful trials within 8 attempts (ACLx0 mean = 5.2 attempts; ACLx1 mean = 6.4 attempts; ACLx2 mean = 4.8 attempts).

Time of return to play (ie, the time point when patients completed the hop testing for this study) was based on physician clearance of each patient to return to full activity after his or her primary ACLR. Return to play criteria at our clinic requires patients to complete a 3-week agility program and pass a leg press evaluation, in addition to having full knee range of motion and no joint effusion. To satisfactorily complete the leg press evaluation, patients must complete 15 repetitions of a leg press exercise where the knee is moved from neutral to 90° of flexion with their ACLR limb at 100% of their body weight. If the leg press test is not satisfactorily completed or the agility program is not finished, return to play is postponed until criteria are satisfied.

Data Analysis

Raw analog data were processed within Visual 3-dimensional version 4.0 software (C-Motion). Raw EMG signals were high-pass filtered using a fourth-order, zero-lag, Butterworth filter at 12 Hz cutoff frequency, whereas raw force plate data were filtered using a fourth-order, zero-lag, low-pass Butterworth filter at 12 Hz

cutoff frequency. Filtered EMG data were then processed using a root mean square algorithm with a 50-ms moving window.

Dynamic EMG collected during the hopping tasks was normalized to the peak muscle activity that was recorded during dynamic trials.²⁶ Using this normalization technique, all normalized root mean square data were at or below 100% of muscle activity. EMG data were then analyzed during 2 phases of activity: preactivity (100 ms prior to ground contact) and reactivity (250 ms post-ground contact).^{29,32} Ground contact from the force platform was defined as the time when the vertical ground reaction force first exceeded 10 N.²³ The average muscle activity that was collected during pre- and reactivity for the 3 muscles was then calculated and used for statistical analysis.

Muscle Strength

Isokinetic quadriceps and hamstrings muscle strength was assessed for the ACL limb in the ACLx1 and ACLx2 groups and in the dominant limb in the ACLx0 group. Testing was completed as previously described.²⁵ Briefly, participants completed 3 maximum voluntary concentric knee extension/flexion contractions at 60deg/s in a Biodex Dynamometer (Biodex System 3, Biodex Medical Corporation) with 2 minutes rest between each trial. The trial with the largest peak torque for the quadriceps and hamstrings was extracted and used for analysis. While these data were not necessary to achieve the purposes set forth in this study, they were collected and are presented to ensure any potential differences in EMG between groups were not driven by group differences in muscle strength.

Statistical Analysis

One-way analyses of variance were used to analyze group differences (ACLx1, ACLx2, ACLx0) for participant demographics (age, height, mass, time from injury to surgery, time from surgery to test), and for muscle activity (vastus lateralis, biceps femoris, lateral gastrocnemius) during the pre- and reactivity phases. Where appropriate, post hoc independent *t* tests were used. Standard Cohen *d* effect sizes¹² ($d = [\text{group1} - \text{group2}] / \text{pooled SD}$) and 95% CIs were also calculated to determine if statistically significant results between groups were clinically meaningful. The strengths of the effect sizes were interpreted using the guidelines described by Cohen,¹² with values less than 0.5 interpreted as weak, values ranging from 0.5 to 0.79 interpreted as moderate, and values greater than 0.8 interpreted as strong. The alpha level was set a priori at $P \leq 0.05$. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) software version 21.0 (IBM Corp).

RESULTS

Participant Demographics

Patient demographics can be found in Table 1. An overall main effect was detected between groups for age (Age, $F_{2,18} = 13.099$, $P \leq 0.001$). Follow up post hoc independent *t* tests revealed significant differences in age between ACLx1 and ACLx0 ($t_{12} = 3.346$, $d = 1.79$, 95% CI = 1.89-8.96, $P = 0.006$) as well as ACLx2

Table 2. Pre- and reactivity electromyograms (mean $\pm$ SD) and isokinetic quadriceps and hamstrings strength

	Preactivity			Reactivity			Strength	
Group	VL	BF	LG	VL	BF	LG	Quad	Hams
ACLx0	0.23 $\pm$ 0.06	0.38 $\pm$ 0.1	0.32 $\pm$ 0.1	0.58 $\pm$ 0.1	0.47 $\pm$ 0.09	0.38 $\pm$ 0.1	2.33 $\pm$ 0.37	1.42 $\pm$ 0.26
ACLx1	0.18 $\pm$ 0.09	0.48 $\pm$ 0.2	0.36 $\pm$ 0.1	0.38 $\pm$ 0.1*	0.32 $\pm$ 0.1	0.32 $\pm$ 0.1	1.55 $\pm$ 0.60*	1.09 $\pm$ 0.37
ACLx2	0.17 $\pm$ 0.09	0.20 $\pm$ 0.1 [†]	0.22 $\pm$ 0.1	0.40 $\pm$ 0.1*	0.29 $\pm$ 0.1	0.35 $\pm$ 0.2	1.59 $\pm$ 0.39*	1.14 $\pm$ 0.12

ACL, anterior cruciate ligament; ACLx0, no ACL injury group; ACLx1, single ACL injury group; ACLx2, double ACL injury group; BF, biceps femoris; Hams, hamstring; LG, lateral gastrocnemius; Quad, quadriceps; VL, vastus lateralis.

* $P < 0.05$, compared with control.

[†] $P < 0.05$, compared with ACLx1.

and ACLx0 ($t_{12} = 4.96$, $d = 2.66$, 95% CI = 3.68-9.45, $P \leq 0.001$), but no difference for age was found between the ACLx1 and ACLx2 groups ($P = 1.00$). No overall main effect was detected for mass ($P = 0.25$), height ($P = 0.077$), body mass index ($P = 0.69$), time from injury to surgery ($P = 0.19$), time from surgery to test ($P = 0.058$), or Tegner score ($P = 0.83$).

Preactivity

A main effect was detected for biceps femoris preactivity ($F_{2,18} = 3.974$, $P = 0.037$). Post hoc tests revealed that ACLx2 used significantly less preactivity biceps femoris activity as compared with ACLx1 ($t_{12} = 2.752$, $d = 1.49$, 95% CI = 0.30-2.67, $P = 0.018$; Table 2). The difference between biceps femoris preactivity in ACLx1 and ACLx2 revealed a strong effect size ($d = 1.49$) with a 95% CI that did not cross 0 (0.30-2.67), indicating that a true difference in reduced preactivity biceps femoris activity was found in the ACLx1 group as compared with the ACLx2. No other significant differences between groups were detected ($P > 0.05$, Table 2).

Reactivity

A main effect was detected for vastus lateralis reactivity ($F_{2,18} = 3.935$, $P = 0.038$). Post hoc tests revealed differences in vastus lateralis reactivity between ACLx1 and ACLx0 ($t_{12} = 2.798$, $d = 1.50$, 95% CI = 0.31-2.68, $P = 0.016$) as well as ACLx2 and ACLx0 ($t_{12} = 2.416$, $d = 1.29$, 95% CI = 0.14-2.44, $P = 0.033$), wherein all ACL participants (regardless of group) were found to use less vastus lateralis activity than ACLx0 (Table 2). Strong effect sizes with 95% CIs that did not cross zero were found (ACLx1 vs ACLx0, $d = 1.50$, 95% CI = 0.31-2.68; ACLx2 vs ACLx0, $d = 1.29$, 95% CI = 0.14-2.44), indicating that clinically meaningful differences in reduced vastus lateralis activity were found between all ACL participants as compared with ACLx0. No other significant differences between groups were detected ($P > 0.05$, Table 2).

Muscle Strength

Quadriceps strength was found to be different between the ACLx1 and the controls ($P = 0.02$) and between the ACLx2 and the

controls ($P = 0.027$). Strong effect sizes with 95% CIs that did not cross zero were found (ACLx1 vs ACLx0, $d = 1.56$, 95% CI = 0.28-2.63; ACLx2 vs ACLx0, $d = 1.95$, 95% CI = 0.57-3.05), indicating that clinically meaningful differences in reduced quadriceps strength were found between all ACL participants as compared with ACLx0. No difference in quadriceps strength was noted between the ACLx1 and ACLx2 groups ($P = 0.999$). Furthermore, no difference in hamstring strength was noted between any of the 3 groups (ACLx1 vs ACLx0, $P = 0.108$; ACLx2 vs ACLx0, $P = 0.22$; ACLx1 vs ACLx2, $P = 0.999$).

DISCUSSION

The purpose of this investigation was to compare muscle activation of the lower extremity muscles during a dynamic hopping task among individuals with a single ACL injury (ACLx1), individuals who went on to have secondary ipsilateral ACL injury (ACLx2), and healthy controls (ACLx0) at a time when individuals were cleared for return to play postprimary ACLR. Understanding if alterations in muscle activity are present at return to play is clinically important because neuromuscular function is a modifiable factor that can be ameliorated with therapy.^{14,20} Furthermore, given that alterations in neuromuscular activity influence biomechanical movement, it is important to understand how muscle activity differs in individuals that go on to experience a secondary ACL injury, as this information can be used by clinicians to intervene and possibly decrease the occurrence of secondary ACL injuries.^{2,8} As anticipated, we found that quadriceps muscle activity during landing was diminished in all ACL participants as compared with ACLx0 (Table 2). Interestingly, it was also found that individuals who did not experience a secondary ipsilateral ACL reinjury (ACLx1) used greater levels of hamstring activity prior to landing than those who went on to have reinjury (ACLx2). We propose that this strategy may have been used as a protective mechanism to dynamically stabilize the reconstructed limb just prior to landing. To our knowledge, this is the first investigation that has prospectively measured alterations in muscle activity at return to play in ACLR individuals.

Preactivity

We found that individuals who went on to sustain a secondary ipsilateral ACL injury (ACLx2) displayed reduced biceps femoris muscle activity during the preactivity phase of the dynamic hopping task (Table 2) as compared with ACLx1. This result was not anticipated, as we had expected that all ACLR individuals would display reduced lower extremity muscle activity as compared with healthy controls. Conversely, it was found that ACLx1 used higher levels of hamstring muscle activity prior to landing than ACLx2, but not than ACLx0 (Table 2). We consider this result to be a novel finding, as it indicates that greater levels of hamstring muscle activity immediately prior to landing may be a factor that helps prevent reinjury. Furthermore, we believe that this is a promising result, as hamstring muscle activity is a component of rehabilitation that can be clinically modified.¹ To our knowledge, no other investigation has prospectively examined alterations in muscle activity at return to play in ACLR individuals.

Based on our work, we theorize that increased biceps femoris activity during the preactivity phase may be a strategy used by individuals to increase joint stability and therefore, enhance the protection of the knee from further injury. Work done by Bulgheroni et al,⁶ in ACL-deficient individuals, in part, helps support our theory as investigators found that hamstring activity was higher in individuals who had suffered an ACL injury when compared with healthy controls during a walking task. Similar to our theory, Bulgheroni et al⁶ also theorized that increased hamstring activity influences knee joint stability by potentially reducing aberrant movement patterns of the knee joint. Importantly, it should be emphasized that work emerging from this data set is preliminary, and future studies that longitudinally investigate (eg, 1, 2, 3 years postsurgery) individuals who are successful postprimary ACLR (ie, do not experience a reinjury) need to be conducted in order to confirm or refute our findings. While assessing the actual biomechanics during the landing was not the focus of this investigation, we do have data that show both knee flexion (ACLx1 mean = 11° and ACLx2 mean = 10°) and hip flexion (ACLx1 = 33° and ACLx2 = 36°) angles were similar at the time of ground contact, which suggests knee landing position does not likely explain why hamstring activity differed between the ACLx1 and ACLx2 groups.

Reactivity

During reactivity, it was found that individuals with ACL injuries displayed reduced vastus lateralis activity as compared with healthy individuals (Table 2). These findings support our original hypothesis wherein we had anticipated that all ACL individuals would use less muscle activity during landing as compared with healthy matched controls.^{11,20} Given that ACL patients had less quadriceps strength than the controls, this finding seems rational, as ACL patients are weaker to begin with and thus are likely less capable of activating their muscles compared with the control participants. Importantly, this result of reduced vastus lateralis activity is in agreement with previous investigations.^{15,19} Specifically, it has been found that

ACL-deficient individuals displayed lower quadriceps muscle activation as compared with healthy controls during dynamic activities such as downhill walking, running, hopping, and landing. Along the same lines, Ciccotti et al¹⁰ compared 3 groups of individuals (healthy, ACLR, and ACL deficient) and found that during running, individuals in the ACLR and ACL-deficient groups used decreased vastus lateralis activity as compared with controls. Similarly, Bulgheroni et al⁶ observed a decrease in quadriceps activity on heel strike in ACL-deficient individuals as well as a reduction in quadriceps activity after the loading stage in ACLR individuals.⁵ Thus, our findings help reaffirm the current literature, which shows that reductions in quadriceps muscle activity are common post-ACLR. Importantly, from a clinical perspective, these reductions in quadriceps muscle activity are potentially hazardous, as less quadriceps activity is thought to lead to reinjury and may contribute to the development of posttraumatic osteoarthritis.²⁶

Clinical Significance

Based on our results, it is recommended that clinicians continue to employ rehabilitation protocols that are capable of positively influencing quadriceps muscle function, as reduced quadriceps muscle activity was found among all ACLR individuals. Furthermore, it appears that hamstring muscle activity is likely an important protective factor of those that are successful (ie, do not go on to reinjury) postprimary ACLR. A particular strength of our work is that the dynamic hopping task used in this study mimics movement characteristics of individuals at return to play. Thus, we believe this data set is reflective of the type of muscle activity that is used during sport. Importantly, it is known that muscle activity can be altered through neuromuscular manipulations such as perturbation training, which has been shown to positively influence and mediate change in muscle activity.^{9,14,16,19} Thus, including perturbation training along with traditional standard of care ACL rehabilitation may promote more appropriate activation of the quadriceps and hamstrings during landing. Similarly, work by Elias et al¹⁵ has shown that verbal instructions can lead to changes in muscle activity and co-contraction during landings in patients after ACLR, further demonstrating the potential to modify the hamstring activation pattern demonstrated by the ACLx2 group.

Limitations

Our work is not without limitations. Ideally, a better age-matched group of controls would have been used to eliminate variations between the ACL and control groups, such as potential maturational effects on neuromuscular control.^{4,24,27} However, it should be pointed out that the age difference between the controls and ACL groups (x1 and x2) do not influence the primary finding of this study, that hamstring preactivity is different between the ACLx1 and ACLx2 group (no age difference was found between the ACLx1 and ACLx2 groups). With that said, maturation is not purely age based, as you can have a younger patient (eg, 15 years old) who is skeletally mature and an older patient (eg, 17 years old) who is not; and

therefore, future studies may want to take into account the skeletal maturity of patients when conducting neuromuscular-based studies. Second, the sample size in this preliminary investigation is small and prevented additional factors (eg, time to peak amplitudes and biomechanics) from being included because of the statistical shortcomings with making multiple comparisons with a small N (eg, increased likelihood of a type II statistical error) and thus larger studies should consider additional variables that may influence ACL reinjury. Given the very limited data on ACL reinjury, it is difficult to complete an adequate a priori power analysis. Our sample size is similar to that of others asking related questions.⁷ Third, patients at our clinic were returned to activity after completing a leg press test and after completion of an agility protocol. The return guidelines at our clinic do not match those recommended in the literature.¹⁸ We would contend, however, that while our criteria to return to activity may differ from those recommended, our patients are reflective of the typical ACL patient returned to activity or sport. The return-to-sport criteria set forth by the Oslo-Delaware collaboration are rigorous, and only ~24% of patients in their study passed their criteria. We do believe the stronger guidelines are necessary for return to sport/activity after ACLR and encourage clinicians to follow the criteria recommended by Grindem et al.¹⁸ Last, it is possible that patients placed into the ACLx1 group could go on to injure their ACL at a time point after the data are published. All ACL patients were followed for at least 3 years postsurgery (range = 3 years 2 months to 7 years 2 months; average = 4 years 1 month).

CONCLUSION

The significant increase in hamstring muscle activity between ACLx1 as compared with ACLx2 during preactivity may be a potential stabilization mechanism utilized to prevent further injury in the ACLx1 participants. The decreased quadriceps activity in all ACLR individuals compared with controls is concerning given that restoring quadriceps muscle function is a primary goal of ACL rehabilitation. These results reinforce that clinicians must continue to incorporate strategies capable of improving quadriceps muscle function post-ACLR and that higher levels of hamstring preactivity may be protective of ACL reinjury.

REFERENCES

- Ageberg E. Consequences of a ligament injury on neuromuscular function and relevance to rehabilitation—using the anterior cruciate ligament-injured knee as model. *J Electromyogr Kinesiol*. 2002;12:205-212.
- Arna Risberg M, Lewek M, Snyder-Mackler L. A systematic review of evidence for anterior cruciate ligament rehabilitation: how much and what type? *Phys Ther*. 2004;5:125-145.
- Barber-Westin SD, Noyes FR. Objective criteria for return to athletics after anterior cruciate ligament reconstruction and subsequent reinjury rates: a systematic review. *Phys Sportsmed*. 2011;39(3):100-110.
- Beunen G, Malina RM. Growth and physical performance relative to the timing of the adolescent spurt. *Exerc Sport Sci Rev*. 1988;16:503-504.
- Briggs KK, Lysholm J, Tegner Y, Rodkey WG, Kocher MS, Steadman JR. The reliability, validity, and responsiveness of the Lysholm score and Tegner activity scale for anterior cruciate ligament injuries of the knee: 25 years later. *Am J Sports Med*. 2009;37:890-897.
- Bulgheroni P, Bulgheroni MV, Andriani L, Guffanti P, Giughello A. Gait patterns after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 1997;5:14-21.
- Capin JJ, Khandha A, Zarzycki R, Manal K, Buchanan TS, Snyder-Mackler L. Gait mechanics and second ACL rupture: implications for delaying return-to-sport. *J Orthop Res*. 2016;35:1894-1901.
- Chaudhari AM, Briant PL, Bevil SL, Koo S, Andriacchi TP. Knee kinematics, cartilage morphology, and osteoarthritis after ACL injury. *Med Sci Sports Exerc*. 2008;40:215-222.
- Chmielewski TL, Hurd WJ, Rudolph KS, Axe MJ, Snyder-Mackler L. Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament rupture. *Phys Ther*. 2005;85:740-749.
- Ciccotti MG, Kerlan RK, Perry J, Pink M. An electromyographic analysis of the knee during functional activities. II. The anterior cruciate ligament-deficient and -reconstructed profiles. *Am J Sports Med*. 1994;22:651-658.
- Cimino F, Volk BS, Setter D. Anterior cruciate ligament injury: diagnosis, management, and prevention. *Am Fam Physician*. 2010;82:917-922.
- Cohen J. *Statistical Analysis for the Behavioral Sciences*. New York, NY: Academic Press; 1977.
- Delagi EF, Iazzetti J, Perotto A, Morrison D. *Anatomic Guide for the Electromyographer*. Springfield, IL: Charles C Thomas; 1981.
- Di Stasi S, Myer GD, Hewett TE. Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. *J Orthop Sports Phys Ther*. 2013;43:777-792.
- Elias ARC, Hammill CD, Mizner RL. Changes in quadriceps and hamstring co-contraction following landing instruction in patients with ACL reconstruction. *J Orthop Sports Phys Ther*. 2015;45:273-280.
- Fitzgerald GK, Axe MJ, Snyder-Mackler L. The efficacy of perturbation training in nonoperative anterior cruciate ligament rehabilitation programs for physically active individuals. *Phys Ther*. 2000;80:128-140.
- Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg*. 2000;8:141-150.
- Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *Br J Sports Med*. 2016;50:804-808.
- Hartigan E, Axe MJ, Snyder-Mackler L. Perturbation training prior to ACL reconstruction improves gait asymmetries in non-copers. *J Orthop Res*. 2009;27:724-729.
- Hewett TE, Di Stasi S, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2013;41:216-224.
- Kievit AJ, Freerk JJ, Barentsz JH, Blankevoort L. A cross-sectional study comparing the rate of osteoarthritis, laxity and quality of life in primary and revision anterior cruciate ligament reconstructions. *Arthroscopy*. 2013;29:898-905.
- Linko E, Harilainen A, Malmivaara A, Seitsalo S. Surgical versus conservative intervention for anterior cruciate ligament rupture in adults. *Cochrane Database Syst Rev*. 2005;2:CD001356.
- McLean SG, Felin RE, Suedekum N, Calabrese G, Passerallo A, Joy S. Impact of fatigue on gender-based high-risk landing strategies. *Med Sci Sports Exerc*. 2007;39:502-514.
- Naughton G, Farpour-Lamber NJ, Carlson J, Bradney M, Van Praagh E. Physiological issues surrounding the performance of adolescent athletes. *Sports Med*. 2000;30:309-325.
- Palmieri-Smith RM, Lepley LK. Quadriceps strength asymmetry following anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. *Am J Sports Med*. 2015;43:1662-1669.
- Palmieri-Smith RM, McLean SG, Ashton-Miller JA, Wojtyś EM. Association of quadriceps and hamstrings cocontraction patterns with knee joint loading. *J Athl Train*. 2009;44:256-263.
- Roemmich JN, Rogol AD. Physiology of growth and development: its relationship to performance in the young athlete. *Clin Sports Med*. 1995;14:483-502.
- Rudolph KS, Axe MJ, Buchanan TS, Scholz JP, Snyder-Mackler L. Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surg Sports Traumatol Arthrosc*. 2001;9:62-71.
- Russell KA, Palmieri RM, Zinder SM, Ingersoll CD. Sex differences in valgus knee angle during a single-leg drop jump. *J Athl Train*. 2006;41:166-171.

-
30. Solomonow M, Baratta R, Zhou BH, et al. The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. *Am J Sports Med.* 1987;15:207-213.
 31. Spindler KP, Huston LJ, Wright RW, et al. The prognosis and predictors of sports function and activity at minimum 6 years after anterior cruciate ligament reconstruction: a population cohort study. *Am J Sports Med.* 2011;39:348-359.
 32. Swanik CB, Lephart SM, Giraldo JL, Demont RG, Fu FH. Reactive muscle firing of anterior cruciate ligament-injured females during functional activities. *J Athl Train.* 1999;34:121-129.
 33. Webster KE, Gonzalez AR, Feller JA. Dynamic joint loading following hamstring and patellar tendon anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2004;12:15-21.
-

For article reuse guidelines, please visit SAGE's website at <http://www.sagepub.com/journals-permissions>.