Fatigue’s Lack of Effect on Thigh-Muscle Activity in Anterior Cruciate Ligament–Reconstructed Patients During a Dynamic-Landing Task

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**Context**: As individuals returning to activity after anterior cruciate ligament reconstruction (ACLr) likely experience fatigue, understanding how fatigue affects knee-muscle activation patterns during sport-like maneuvers is of clinical importance. Fatigue has been suggested to impair neuromuscular control strategies. As a result, fatigue may place ACLr patients at increased risk of developing posttraumatic osteoarthritis (OA).

**Objective**: To determine the effects of fatigue on knee-muscle activity post-ACLr. **Design**: Case control. **Setting**: University laboratory. **Participants**: 12 individuals 7–10 mo post-ACLr (7 male, 5 female; age 22.1 ± 4.7 y; 1.8 ± 0.1 m; mass 77.7 ± 11.9 kg) and 13 controls (4 male, 9 female; age 22.9 ± 4.3 y; 1.7 ± 0.1 m; mass 66.9 ± 9.8 kg). **Interventions**: Fatigue was induced via repetitive sets of double-leg squats (n = 8), which were interspersed with sets of single-leg landings (n = 3), until squats were no longer possible. **Main Outcome Measures**: 2 × 2 repeated-measures ANOVA was used to detect the main effects of group (ACLr, control) and fatigue state (prefatigue, postfatigue) on quadriceps:hamstring cocontraction index (Q:H CCI). **Results**: All subjects demonstrated higher Q:H CCI at prefatigue compared with postfatigue (F(1,23) = 66.949, P ≤ .001). Q:H CCI did not differ between groups (F(1,23) = 0.599, P = .447). **Conclusions**: The results indicate that regardless of fatigue state, ACLr individuals are capable of restoring muscle-activation patterns similar to those in healthy subjects. As a result, excessive muscle cocontraction, which has been hypothesized as a potential mechanism of posttraumatic OA, may not contribute to joint degeneration after ACLr.

**Keywords**: quadriceps, hamstring, cocontraction, knee

Posttraumatic osteoarthritis (OA) is a long-term consequence of anterior cruciate ligament (ACL) injury. Current evidence suggests that up to 70% of patients with ACL injuries will develop radiographic evidence of osteoarthritis 5 to 14 years after ACL reconstruction (ACLr). Suggested mechanisms of posttraumatic OA include persistent quadriceps weakness, mechanical instability, altered neuromuscular control, and structural changes to the knee joint, such as subchondral bone contusions and/or meniscal injury. Given that altered neuromuscular control after ACL injury may be modifiable, it is important to identify such changes and target interventions to restore preinjury control strategies. Excessive quadriceps:hamstring cocontraction has been theorized to be a potential precursor to idiopathic OA and could also be a contributing factor to the development of OA after joint injury. Heightened muscle cocontraction can result in higher joint contact forces and reduced knee-joint motion leading to higher impact loads, which in turn may contribute to the breakdown of joint tissues. It has been shown that ACL-deficient patients use higher muscle cocontraction during walking, jogging, and hopping activities. This muscle-activation strategy adopted by ACL-deficient patients is hypothesized to occur to provide additional dynamic knee-joint stability. Currently, it is not clear if this control strategy continues after ACLr and could possibly contribute to the genesis of posttraumatic OA.

Return to sport is a common goal of patients who have undergone ACLr. As fatigue is inevitable in sport, understanding its impact on neuromuscular control of ACLr patients is of clinical importance. Available literature demonstrates that fatigue alters quadriceps and hamstring muscle-activation patterns in healthy individuals, but there is little evidence to establish what effect fatigue has on the ACLr population during dynamic movement. Given that the dynamic (muscles) and static components (ligaments and joint capsule) of knee stability are altered post-ACLr, it seems plausible that in an attempt to stabilize the knee, ACLr individuals use higher levels of muscle cocontraction to enhance joint stability. In fact, the effects of fatigue that occur cumulatively during the course of competition may compromise neuromuscular control to a point where abnormal muscle responses are unavoidable. As a result, fatigue may induce even higher...
levels of muscle cocontraction, potentially resulting in higher forces being delivered to the articular cartilage during landing. As such, the very strategy that may be employed by individuals after ACL injury to stabilize the knee could play a part in the mechanism that leads to joint degeneration.

Therefore, the purpose of this investigation was to examine the differences in neuromuscular control strategies employed by ACLr and healthy individuals during a dynamic jump-landing task and the effect fatigue has on these muscle-activation patterns. We hypothesized that ACLr subjects would use higher levels of quadriceps:hamstring muscle cocontraction in the reconstructed limb than control subjects. In addition, we hypothesized that the ACLr group would demonstrate higher levels of muscle cocontraction at postfatigue than prefatigue.

Materials and Methods

Participants

Twelve individuals 7 to 10 months post-ACLr and 13 control subjects participated in this study (Table 1). Potential ACLr subjects were excluded if they had a history of lower extremity surgery other than their recent ACLr, had suffered a lower extremity injury since undergoing ACLr, had current pain in either knee, had undergone a meniscal repair or meniscectomy with their ACLr, had experienced grade II to III concomitant ligament damage with their ACL injury, or had a known heart condition. Pregnant women were also excluded. Control subjects were excluded if they had a history of ACL injury or reconstruction, had current pain in either knee, or had suffered a lower extremity injury in the previous 6 months.

Written, informed consent was obtained from all subjects before testing.

Experimental Design

This cross-sectional study had 2 independent variables: group (ACLr and control) and fatigue state (prefatigue and postfatigue). The main outcome measures were the quadriceps:hamstring muscle cocontraction index and normalized root-mean-square electromyography (EMG) for the vastus lateralis and lateral hamstring muscles.

Testing Procedures

To record muscle activity, the skin for each electrode site was shaved and cleaned with isopropyl alcohol. Surface EMG electrodes (DE-2.1, Delsys Inc, Boston, MA) with a 10-mm interelectrode distance were secured over the muscle bellies of the vastus lateralis and lateral hamstring muscles, according to the technique described by Delagi et al. A ground electrode was placed on an olecranon process. Raw EMG data were collected using a commercial EMG system (Bagnoli 16-channel, Delsys) sampling at 1200 Hz during dynamic activity and also during maximum voluntary isometric contractions (MVICs) for the purposes of normalization. Quadriceps and hamstring MVICs were performed while seated with the knee in 90° of flexion. Resistance was applied above the ankle by the examiner while the subject performed 1 MVIC, either kicking out (quadriceps) or in (hamstrings) as hard as possible for approximately 15 seconds.

After collection of the MVICs, subjects were given instruction in how to perform the dynamic landing task and were then provided time to practice the task to ensure adequate familiarization. The landing task required subjects to perform a double-leg forward jump over a 17-cm box and land on single leg on a force plate (OR 6-7, Advanced Medical Technology, Inc, Watertown, MA) sampling at 1200 Hz located 1 m away. On landing, subjects immediately and aggressively jumped laterally to the opposite side (Figure 1). The limb on which subjects landed was randomly determined using a custom-written LabVIEW program software version 8.5 (National Instruments, Austin, TX) that was displayed on a computer screen visible to the subjects before takeoff. Specifically, if the subject landed on his or her right limb, a light was displayed on the right side of the computer screen and the subject would jump forward, land on his or her right limb on a force platform, and then laterally jump to the left. Three good trials, defined as the proper limb landing completely on the force platform, were analyzed.

Immediately after the prefatigue trials, subjects began the fatigue protocol. To induce fatigue, subjects were required to perform sets of 8 double-leg squats. They were asked to squat to approximately 90° of knee flexion, at a self-selected pace and without resistance, while the investigator provided continuous verbal feedback regarding knee-joint flexion angle during the fatiguing exercise. After each set of 8 squats, subjects were required to perform 3 dynamic landings, similar to the prefatigue landing trials.

Subjects continued performing the sets of squats followed by dynamic landings until maximal fatigue was achieved, defined as the point at which they could no longer perform 5 consecutive squats to 90° of knee flexion without assistance and/or could no longer consistently reach the force platform during the dynamic landing task. If a subject was unable to reach the force platform at maximal fatigue, then the 3 trials immediately before maximal fatigue were used for analysis. The 3 landing trials before the initiation of the fatigue protocol (prefatigue trials) and the last 3 successful trials after the fatigue protocol (postfatigue trials) were analyzed and used in data analysis.

There was no limit to the number of squats a subject could perform to reach maximal fatigue. The fatiguing exercise was discontinued in cases where ACLr subjects reported pain in their reconstructed knee (n = 1). The fatigue protocol and dynamic landing task used for this investigation were based on previous work by McLean and Samorezov, where fatigue was induced via sets of 3 single-leg landings rather than the sets of 8 double-leg
### Table 1 Participant Demographics, Mean ± SD

<table>
<thead>
<tr>
<th>Group</th>
<th>Participants</th>
<th>Sex</th>
<th>Age (y)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
<th>Time from ACL injury to ACLr (d)</th>
<th>Time to test post-ACLr (d)</th>
<th>Graft type</th>
<th>Grade I collateral ligament injury</th>
<th>Debridement of meniscus</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACLr n = 12</td>
<td>7 m, 5 f</td>
<td>22.1 ± 4.7</td>
<td>1.8 ± 0.1</td>
<td>77.7 ± 11.9</td>
<td>75.1 ± 54.9</td>
<td>248 ± 54.6</td>
<td>PT = 7</td>
<td>STG = 5</td>
<td>MCL = 4, LCL = 1, both = 1</td>
<td>lateral = 2, medial = 0, both = 1</td>
</tr>
<tr>
<td>Control n = 13</td>
<td>4 m, 9 f</td>
<td>22.9 ± 4.3</td>
<td>1.7 ± 0.1</td>
<td>66.9 ± 9.8</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Abbreviations: ACL indicates anterior cruciate ligament; ACLr, ACL reconstruction; PT, patellar tendon; STG, semitendinosus/gracilis; MCL, medial collateral ligament; LCL, lateral collateral ligament; NA, not applicable.
landings used in the current study. Given that our subjects were not college athletes and had recently undergone surgery, we determined, based on pilot testing, that double-leg squats were more reasonable for our subjects to do repeatedly.

Data Analysis

EMG data were band-pass filtered using a fourth-order, zero-lag Butterworth filter with high- and low-pass cutoff frequencies of 10 and 500 Hz, respectively. EMG data were then processed using a root-mean-square algorithm with a 50-millisecond moving window. Dynamic EMG data recorded during the landing task were normalized to the larger of the peak muscle activity recorded during the MVIC or the peak muscle activity recorded during the dynamic landing trials. Using this normalization technique, all normalized root-mean-square data during the dynamic landing task were at or below 100% of maximal activation. Dynamic muscle activity was analyzed at the time between ground contact to 250 milliseconds after ground contact. Muscle cocontraction, operationally defined as the simultaneous activation of 2 muscles, was assessed between the vastus lateralis and lateral hamstring. EMG cocontraction was determined using the following equation as described by Rudolph et al:

\[
\frac{\text{EMGS}}{\text{EMGL}} \times (\text{EMGS} + \text{EMGL})
\]

where EMGS was the level of activity in the less active muscle and EMGL was the level of activity in the more active muscle. The index was then multiplied across the sum of the 2 muscles, to provide an estimate of the relative level of cocontraction. The index was applied to each data sample, and the resulting curves were averaged over the time between ground contact to 250 milliseconds after ground contact and used in the analysis.

Statistical Analysis

We used 2 × 2 repeated-measures analysis of variance (ANOVA) to detect the main effects of group (ACLr, control) and fatigue state (prefatigue, postfatigue) on quadriceps:hamstring muscle cocontraction index, quadriceps activity, and hamstring activity. Where appropriate, post hoc Bonferroni multiple-comparison procedures were used. Standard Cohen $d$ effect sizes ($d = [\text{ACLr} - \text{control}] / \text{pooled SDs}$) and 95% confidence intervals were calculated to assess group differences in quadriceps:hamstring muscle cocontraction index, quadriceps activity, and hamstring activity at prefatigue and postfatigue. The strength of the effect sizes was interpreted using the guidelines described by Cohen.8
with values less than .5 interpreted as weak, values ranging from .5 to .79 interpreted as moderate, and values greater than .8 interpreted as strong. An independent t test was used to determine if the ACLr group reached maximal fatigue faster than the control group. The α level was set a priori at $P \leq .05$. Statistical analysis was performed using the Statistical Package for the Social Sciences (SPSS) software version 18.0 (SPSS, Inc, Chicago, IL).

**Results**

**Cocontraction Index**

A main effect for fatigue state was found, which demonstrates that all subjects had significantly higher quadriceps:hamstring muscle cocontraction indices at prefatigue than at postfatigue ($F_{1,23} = 66.949, P \leq .001$). The main effect for group ($F_{1,23} = 0.599, P = .447$; Figure 2) and the interaction of group × fatigue state were not found to be significant ($F_{1,23} = 1.454, P = .240$). Standardized effect sizes calculated between groups at prefatigue and postfatigue are shown in Table 2.

**Quadriceps and Hamstring Activity**

Fatigue was found to have an effect on quadriceps and hamstring muscle activity. Specifically, all subjects had significantly higher quadriceps and hamstring activity at prefatigue than at postfatigue (quadriceps, $F_{1,23} = 41.523, P \leq .001$; hamstring, $F_{1,23} = 55.640, P \leq .001$). Differences between groups were also noted for quadriceps activity. ACLr participants used less quadriceps activity than controls regardless of fatigue state ($F_{1,23} = 7.974, P = .010$). While no group effects were noted for hamstring activity, a trend toward higher hamstring muscle activity was found in the ACLr group than in controls regardless of fatigue state ($F_{1,23} = 4.028, P = .057$; Figure 3). Furthermore, the interactions of group × fatigue state on quadriceps and hamstring muscle activity were not significant (quadriceps, $F_{1,23} = 0.211, P = .651$; hamstring, $F_{1,23} = 0.124, P = .728$). Standardized effect sizes calculated between groups at prefatigue and postfatigue are shown in Table 2.

**Number of Squats to Fatigue**

The number of squats subjects were able to perform to reach maximal fatigue did not differ between groups.

![Figure 2](image-url) — Quadriceps-to-hamstring cocontraction index (QH CCI) for anterior cruciate ligament–reconstructed (ACLr) and control participants, mean ± SD. All subjects demonstrated significantly higher QH CCI at prefatigue than postfatigue (*$P \leq .001$). QH CCI did not differ between groups ($P = .447$).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Prefatigue</th>
<th>Postfatigue</th>
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<tbody>
<tr>
<td>Quadriceps:hamstring cocontraction index</td>
<td>0.04 (–0.74, 0.83), weak</td>
<td>0.45 (–0.34, 1.24), weak</td>
</tr>
<tr>
<td>Quadriceps activity</td>
<td>–1.29 (–2.15, –0.43), strong</td>
<td>–0.69 (–1.50, 0.12), moderate</td>
</tr>
<tr>
<td>Hamstring activity</td>
<td>0.63 (–0.17, 1.43), moderate</td>
<td>0.71 (–0.10, 1.52), moderate</td>
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</table>
This investigation was conducted to determine if ACLr individuals use different levels of quadriceps:hamstring muscle cocontraction than healthy subjects during a dynamic landing task. A secondary objective was to examine the effect of fatigue on ACLr muscle-activation patterns. The main findings of our study suggest that ACLr individuals are capable of utilizing levels of muscle cocontraction similar to those of healthy subjects during a landing task, regardless of fatigue state. This indicates that excessive muscle cocontraction, which has been theorized as a potential mechanism to posttraumatic OA after ACLr, may not play a role in the progression of joint degeneration.

We hypothesized that ACLr subjects would use higher levels of muscle cocontraction than control subjects during a dynamic landing task; however, this was not supported by our data. Previous findings indicate that ACL-deficient individuals use higher levels of muscle cocontraction than healthy control subjects. This neuromuscular strategy used by ACL-injured patients is hypothesized to occur to provide additional joint stability. Given that ACLr patients have been shown to return to activity with ligament stiffness, muscle strength, and joint biomechanics (all of which have the potential to influence joint stability) that are not equivalent to those of healthy individuals, it seems plausible that increased muscle cocontraction may be a strategy called on to enhance joint stability. Our findings did not support this contention. As ACLr is considered to restore static stability, quantified by a lack of pathological ligament laxity, it is conceivable that additional measures such as increased muscle cocontraction to provide dynamic stability to the joint are not necessary. Similar to our results, Lustosa et al observed that ACLr individuals who had returned to their preinjury activity level did not display increased quadriceps:hamstring muscle cocontraction in response to a perturbation. Thus, while our result was unexpected, our data seem to agree with current literature and support the idea that ACLr patients are capable of utilizing muscle cocontraction patterns similar to those of healthy young adults.

Our results indicate that the magnitude of cocontraction declined from prefatigue to postfatigue in both ACLr and control subjects, suggesting that fatigue does not lead to greater magnitudes of cocontraction, as we had hypothesized. Our findings seem to agree with the work of others. Padua et al found that fatiguing healthy participants led to an increase in the quadriceps:hamstring muscle cocontraction ratio, while Hautier et al found an overall reduction in muscle coactivation in healthy adults after fatigue. While differences in study design, subject populations, and measurements could account for the discrepancies among studies, a decline in muscle coactivation has been attributed to better modulation of quadriceps and hamstring muscle activity to cope with the onset of fatigue. Based on the limited evidence available to document the effects of fatigue in an ACLr population, it appears that more research may be necessary to better understand the influence of fatigue on muscle activity after ACLr.

All subjects used higher quadriceps and hamstring activity at prefatigue than at postfatigue. This utilization of less muscle activity postfatigue may be the result of...
an inhibitory reflex that is evoked in the quadriceps and hamstring muscles. Woods et al.35 suggest that such an inhibitory reflex may arise due to changes in the contractile properties of the muscle or the metabolites from prefatigue to postfatigue and that the consequent reduction in net motoneuron discharge will ultimately cause a reduction in the muscle’s net force production. It is also possible that fatigue induces a decline in quadriceps and hamstring muscle activity due to a reduction in muscle motoneuron discharge rate and frequency.39

Regardless of fatigued state, our results showed that ACLr participants used lower levels of quadriceps muscle activity than control subjects. In addition, a trend emerged suggesting that ACLr individuals may use higher levels of hamstring muscle activity, but it was found not to be statistically significant (P = .057). Therefore, while ACLr individuals maintained levels of cocontraction similar to those of controls, it appears they used less quadriceps and more hamstring muscle activation overall. This deficiency in quadriceps neuromuscular control and subsequent facilitation in hamstring activity is not a new finding. Previous investigations using experimentally effused knee joints,50,51 ACL-deficient individuals,26,52 and ACLr populations26 have shown the antagonist response of the hamstring when quadriceps weakness is present. The trend toward facilitation in hamstring activity is thought to occur as a protective mechanism used by individuals after injury (or simulated effusion) and ACLr in an effort to reduce anterior tibial translation and assist the ACL graft.35

Higher levels of quadriceps:hamstring muscle cocontraction post-ACLr have been suggested to contribute to posttraumatic OA. The results from this investigation contest this theory as a possible mechanism for posttraumatic OA. Given that we did not find higher levels of muscle cocontraction among ACLr individuals postfatigue than at prefatigue or than in control subjects, other factors may play a more causal role in the development of knee-joint degeneration after ACL injury. Subchondral bone contusions,13-15 meniscal injury,16-18 and persistent quadriceps weakness8–10 are all proposed mechanisms of posttraumatic OA that likely could provide greater contributions to the overall OA progression postinjury. To best isolate the factors that contribute to posttraumatic OA after ACL injury, more research is needed so clinicians and surgeons alike can develop the most effective rehabilitation protocols to improve long-term knee-joint health.

This study was not without limitations. First, individuals who underwent both patellar-tendon (n = 7) and semitendinosus/gracilis autograft (n = 5) ACLr were included in this study and may have affected our results. Although this study was not powered to consider graft type as an independent variable, we did provide descriptive data for our dependent variables separated by graft type (Table 3). These data suggest that the patellar-tendon and semitendinosus/gracilis participants had similar levels of muscle activity that decline from prefatigue to postfatigue. To date, it is unknown what effect graft type has on muscle fatigability. Future investigations are warranted to determine the potential differences between graft type and response to fatigue. Second, the fatigue protocol used in this investigation did not reproduce sport participation. Although our fatigue protocol incorporated a double-leg squatting motion similar to movement that would be performed during activity, it is plausible that ACLr subjects may respond differently to fatigue during an actual sporting event than during a controlled laboratory setting. Third, calculations of standardized effect sizes and 95% confidence intervals revealed weak to small effect sizes with wide confidence intervals for the muscle cocontraction index. We interpret this to mean that even with a larger sample size, the effect of ACLr on muscle cocontraction would likely be small. It is important to note that our sample size was similar to those of other investigations examining muscle activity in patients after ACL injury and surgery.22,26,43,53,54 Future investigations should be conducted to help solidify the effect of fatigue on muscle activity in patients after ACLr.

## Conclusion

ACLr individuals are capable of utilizing levels of quadriceps:hamstring muscle cocontraction similar to those of healthy subjects during a landing task. Muscle fatigue did, however, lead to declines in quadriceps:hamstring muscle cocontraction in all subjects. Excessive muscle cocontraction, which has been hypothesized as a potential mechanism of posttraumatic OA, may not contribute to joint degeneration after ACLr.

## Acknowledgments

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**Table 3**  ACLr Muscle Activity by Graft Type, Mean ± SD

<table>
<thead>
<tr>
<th>Graft type</th>
<th>Prefatigue</th>
<th>Postfatigue</th>
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<tbody>
<tr>
<td></td>
<td>Q:H CCI</td>
<td>Quadriceps</td>
</tr>
<tr>
<td>PT (n = 7)</td>
<td>43.82 ± 9.27</td>
<td>0.40 ± 0.13</td>
</tr>
<tr>
<td>STG (n = 5)</td>
<td>48.01 ± 5.40</td>
<td>0.43 ± 0.08</td>
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Abbreviations: ACLr indicates anterior cruciate ligament reconstruction; Q:H CCI, quadriceps:hamstring cocontraction index; PT, patellar tendon; STG, semitendinosus/gracilis.
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