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FATIGUE'S LACK OF EFFECT ON THIGH-MUSCLE ACTIVITY IN ANTERIOR CRUCIATE LIGAMENT-RECONSTRUCTED PATIENTS DURING A DYNAMIC-LANDING TASK

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INTRODUCTION

Post-traumatic 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 5-14 years post ACL reconstruction.¹⁻⁷ Suggested mechanisms of post-traumatic OA include persistent quadriceps weakness,⁸⁻¹⁰ mechanical instability,^{11, 12} altered neuromuscular control, and structural changes to the knee joint such as subchondral bone contusions¹³⁻¹⁵ and/or meniscal injury.¹⁶⁻¹⁸

Given that altered neuromuscular control following ACL injury may be modifiable, it is of importance to identify such changes and target interventions to restore pre-injury control strategies. Excessive quadriceps:hamstring muscle co-contraction has been theorized to be a potential precursor to idiopathic OA and could also be a contributing factor to the development of OA following joint injury.¹⁹ Heightened muscle co-contraction can result in higher joint contact forces²⁰ and reduced knee joint motion¹⁹ leading to higher impact loads, which in turn may contribute to the breakdown of joint tissues.²¹⁻²³ It has been shown that ACL deficient patients utilize higher muscle co-contraction during walking,²⁴⁻²⁶ jogging,²² and hopping activities.²⁷ This muscle activation strategy adopted by ACL deficient patients is hypothesized to occur in order to provide additional dynamic knee joint stability.²³ Currently, it is not clear if this control strategy continues following ACL reconstruction (ACLR) and could possibly contribute to the genesis of post-traumatic 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,²⁸ but little evidence is present to establish what affect 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 the in an attempt to stabilize the knee, ACLr individuals may use higher levels of muscle co-contraction . In fact, the enhance joint stability effects of fatigue that occur cumulatively during the course of compet in order to ition may compromise neuromuscular control to a point where abnormal muscular responses are unavoidable. As a result, fatigue may induce even higher levels of muscle co-contraction potentially resulting in higher forces being delivered to the articular cartilage during landing.²⁹ As such, the very strategy that may be employed by individuals following 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 utilize higher levels of quadriceps:hamstring muscle co-contraction in the reconstructed limb when compared to control subjects. In addition, we hypothesized that the ACLr group would demonstrate higher levels of muscle co-contraction at post-fatigue when compared to pre-fatigue.

MATERIALS AND METHODS

Participants

Twelve individuals 7-10 months post-ACLR and thirteen controls 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, underwent a meniscal repair or meniscectomy with their ACLr, experienced grade II-III concomitant ligament damage with their ACL injury, or had a known heart condition. Pregnant females 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 six months. Written, informed consent was obtained from all subjects prior to testing.

Experimental Design

This cross-sectional study had two independent variables including group (ACLR and control) and fatigue state (pre-fatigue and post-fatigue). The main outcome measures were the quadriceps:hamstring muscle co-contraction 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, Mass) with a 10 mm inter-electrode distance were secured over the muscle bellies of the vastus lateralis and

lateral hamstring muscles, according to the technique described by Delagi *et al.*,³⁰ A ground electrode was placed on an olecranon process. Raw EMG data was collected using a commercial EMG system (Bagnoli 16-channel, Delsys) sampling at 1200Hz³¹ during dynamic activity and also during maximum voluntary isometric contractions 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 one MVIC where the subject either kicked out (quadriceps) or in (hamstrings) as hard as possible for approximately 15 seconds.

Following the 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 17cm box and land on single leg on a force plate (OR 6-7; Advanced Medical Technology, Inc, Watertown, MA) sampling at 1200 Hz located one meter away. Upon landing, subjects immediately and aggressively jumped laterally to the opposite side (Figure 1).³² 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 was to land on his/her right limb, a light was displayed on the right side of the computer screen and the subject would jump forward, land on his/her right limb on a force platform and then laterally jump to the left.³³ Three good trials, defined as the proper limb landing completely on the force platform were analyzed.

Immediately following the pre-fatigue trials, subjects began the fatigue protocol. In order to induce fatigue, subjects were required to perform sets of eight double-leg squats. The subjects 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 the subject's knee joint flexion angle during the fatiguing exercise.^{32, 34} Following each set of eight squats, subjects were required to perform three dynamic landings, similar to the pre-fatigue landing trials.

Subjects continued performing the sets of squats followed by dynamic landings until maximal fatigue was achieved, defined as the point at which subjects could no longer perform five consecutive squats to 90° of knee flexion without assistance and/or subjects 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 three trials immediately prior to maximal fatigue were used for analysis. The three landing trials prior to the initiation of the fatigue protocol (pre-fatigue trials) and the last three successful trials following the fatigue protocol (post-fatigue 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 utilized for this investigation were based off the previous work by McLean *et al.*,³² where fatigue was induced via sets of three single-legged landings rather than the sets of eight double-legged landings used in the current study. Given that our subjects were not collegiate athletes and

had recently undergone surgery it was determined, based on pilot testing, that double-legged 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 was then processed using a root mean square (RMS) algorithm with a 50msec 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.³¹ Using this normalization technique, all normalized RMS 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 250msec post ground contact.³⁵ Muscle co-contraction, operationally defined as the simultaneous activation of two muscles, was assessed between the vastus lateralis and lateral hamstring. EMG co-contraction was determined using the following equation as described by Rudolph *et al.*,²²:

$$\frac{EMGS}{EMGL} \times (EMGS + EMGL)$$

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 two muscles, to provide an estimate of the relative level of co-contraction. The index was applied to each data sample, and the resulting curves were averaged over the time between ground contact to 250msec post ground contact and used in the analysis.

Statistical Analysis

We utilized 2x2 repeated measures analysis of variance (ANOVA) to detect the main effects of group (ACLR, control) and fatigue state (pre-fatigue and post-fatigue) on quadriceps:hamstring muscle co-contraction index, quadriceps activity, and hamstring activity. Where appropriate, *post hoc* Bonferroni multiple comparison procedures were used. Standard Cohen's *d* effect sizes³⁶ ($d = (\text{ACLR} - \text{control}) / \text{pooled standard deviations}$) and 95% confidence intervals were calculated to assess group differences in quadriceps:hamstring muscle co-contraction index, quadriceps activity and hamstring activity at pre and post-fatigue. The strength of the effect sizes were interpreted using the guidelines describe by Cohen,³⁶ 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*. An independent t-test was utilized to determine if the ACLR group reached maximal fatigue faster than the control group. The α -level was set *a priori* at $P = 0.05$. Statistical analysis was performed using the Statistical Package for the Social Sciences (SPSS) software version 18.0 (SPSS, Inc., Chicago, IL).

RESULTS

Co-contraction Index

A main effect for fatigue state was found, which demonstrates that all subjects had significantly higher quadriceps:hamstring muscle co-contraction indices at pre-fatigue compared to post-fatigue ($F_{1, 23}=66.949$, $P=0.001$). The main effect for group ($F_{1, 23}=0.599$, $P=0.447$; Figure 2) and the interaction of group x fatigue state were not found to be significant ($F_{1, 23}=1.454$, $P=0.240$). Standardized effect sizes calculated between groups at pre and post-fatigue 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 pre-fatigue compared to post-fatigue (Quadriceps: $F_{1, 23}=41.523$, $P=0.001$; Hamstring: $F_{1, 23}=55.640$, $P=0.001$). Differences between groups were also noted for quadriceps activity. ACLr participants utilized less quadriceps activity than controls regardless of fatigue state ($F_{1, 23}=7.974$, $P=0.010$). While no group effects were noted for hamstring activity, a trend toward higher hamstring muscle activity was found in the ACLr group as compared to controls regardless of fatigue state ($F_{1, 23}=4.028$, $P=0.057$; Figure 3). Further, the interactions of group x fatigue state on quadriceps and hamstring muscle activity was not significant (Quadriceps: $F_{1, 23}=0.211$, $P=0.651$; Hamstring: $F_{1, 23}=0.124$, $P=0.728$). Standardized effect sizes calculated between groups at pre and post-fatigue 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 (ACLR 454.00 ± 266.36 ; control 589.69 ± 318.55 ; $t_{1, 23}=-1.150$, $P=0.262$). This finding indicates that our fatigue protocol was able to induce similar levels of quadriceps and hamstring fatigue across groups at a similar rate, which allowed us to make group comparisons with confidence.

DISCUSSION

This investigation was conducted to determine if ACLr individuals utilize different levels of quadriceps:hamstring muscle co-contraction than healthy subjects during a dynamic landing task. A secondary objective of this investigation was to examine the effect of fatigue on ACLr muscle activation patterns. The main findings of our study suggests that ACLr individuals are capable of utilizing similar levels of muscle co-contraction as compared to healthy subjects during a landing task, regardless of fatigue state. This indicates that excessive muscle co-contraction, which has been theorized as a potential mechanism to post-traumatic OA following ACLr, may not play a role in the progression of joint degeneration.

We hypothesized that ACLr subjects would utilize higher levels of muscle co-contraction than control subjects during a dynamic landing task, however this was not supported by our data. Previous findings indicate that ACL-deficient individuals utilize higher levels of

muscle co-contraction when compared to healthy control subjects.^{22, 24-27} This neuromuscular strategy utilized by ACLr patients is hypothesized to occur in order to provide additional joint stability.²³ Given that ACLr patients have been shown to return to activity with ligament stiffness,³⁷ muscle strength,^{38, 39} and joint biomechanics^{17, 40, 41} (all of which have the potential to influence joint stability) that is not equivalent to healthy persons, it seems plausible that increased muscle co-contraction may be a strategy called upon to enhance joint stability. Our findings did not support this contention. As ACL reconstruction is considered to restore static stability, quantified by a lack of pathological ligament laxity,⁴² it is conceivable that additional measures, such as increased muscle co-contraction, to provide dynamic stability to the joint are not necessary. Similar to our results, Lustosa *et al.*,⁴³ observed that ACLr individuals who had returned to their pre-injury activity level did not display increased quadriceps:hamstring muscle co-contraction in response to a perturbation. Thus, while our result was unexpected, our data seem to agree with current literature and support that ACLr patients are capable of utilizing similar muscle co-contraction patterns as healthy young adults.

Our results indicate that the magnitude of co-contraction declined from pre-to-post fatigue in both ACLr and control subjects, suggesting that fatigue does not lead to greater magnitudes of co-contraction as we had hypothesized. Our findings seem to agree⁴⁴ and disagree⁴⁵⁻⁴⁷ with the work of others. Pauda *et al.*,⁴⁷ found that fatiguing healthy participants led to an increase in the quadriceps:hamstring muscle co-contraction ratio, while Haunter and colleagues⁴⁴ found an overall reduction in muscle co-activation in healthy adults following fatigue. While differences in study design, subject populations, and measurements could account for the discrepancies amongst studies, a decline in muscle co-activation has been attributed to a better modulation of quadriceps and hamstring muscle activity to cope with the onset of fatigue.⁴⁴ Based on the limited evidence available to document the effects of fatigue in an ACLr population, it appears more research may be necessary to better understand the influence of fatigue on muscle activity following ACLr.

All subjects utilized higher quadriceps and hamstring activity at pre-fatigue compared to post-fatigue. This utilization of less muscle activity following fatigue may be the result of an inhibitory reflex that is evoked in the quadriceps and hamstring muscles.⁴⁸ Woods and colleagues⁴⁸ suggests that such an inhibitory reflex may arise due to changes in the contractile properties of the muscle or the metabolites from pre-to-post fatigue, and that the consequent reduction in net motorneuron discharge will ultimately cause a reduction in the muscle's net force production. It is also possible, that fatigue can also induce a decline in quadriceps and hamstring muscle activity due to a reduction in muscle motorneuron discharge rate and frequency.⁴⁹

Regardless of fatigued state, our results showed that ACLr participants utilized smaller 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 ($P=0.057$). Therefore, while ACLr individuals maintained levels of co-contraction that were similar to controls it appears they utilized 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} as well as ACLr populations²⁶ have shown the antagonist response of the hamstring when quadriceps weakness is present. The trends towards facilitation in hamstring activity is thought to occur as a protective mechanism utilized by individuals following 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 co-contraction post-ACLR have been suggested to contribute to post-traumatic OA. The results from this investigation contest this theory as a possible mechanism for post-traumatic OA. Given that we did not find higher levels of muscle co-contraction among ACLr individuals as compared to pre-fatigue values and to control subjects, other factors may play a more causal role in the development of knee joint degeneration following ACL injury. Subchondral bone contusions,¹³⁻¹⁵ meniscal injury,¹⁶⁻¹⁸ and persistent quadriceps weakness,⁸⁻¹⁰ are all proposed mechanisms of post-traumatic OA that likely could provide greater contributions to the overall OA progression post-injury. To best isolate the factors that contribute to post-traumatic OA following 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 autograph (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). This data suggests that the PT and STG participants had similar levels of muscle activity that decline from pre-fatigue to post-fatigue. 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 utilized in this investigation did not reproduce sport participation. Although our fatigue protocol incorporated a double-legged squatting motion that is 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 co-contraction index. We interpret this to mean that even with a larger sample size, the effect of ACLr on muscle co-contraction would likely be small. It is important to note that our sample size was similar to other investigations examining muscle activity in patients post-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 following ACLr.

CONCLUSION

ACLR individuals are capable of utilizing similar levels of quadriceps:hamstring muscle co-contraction as healthy subjects during a landing task. Muscle fatigue did however lead to declines in quadriceps:hamstring muscle co-contraction in all subjects. Excessive muscle co-

contraction, which has been hypothesized as a potential mechanism of post-traumatic OA, may not contribute to joint degeneration following ACLr.

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Figure 1.

Dynamic Landing Task. L1 and L2 represent the images displayed to subjects on the computer screen indicating on which limb the subject was to land. L2 required the subject to land on his or her right leg. Dynamic landings consisted of a double leg take-off onto a single leg landing on a force plate immediately followed by an aggressive lateral cut to the opposite side.

Figure 2.

Quadriceps-to-Hamstring cocontraction index (QH CCI) for anterior cruciate ligament-reconstructed (ACLR) and control participants, mean $\pm$ SD. All subjects demonstrated significantly higher QH CCI at prefatigue compared to postfatigue (* P .001). QH CCI did not differ between groups (P =.447).

Figure 3.

Quadriceps and hamstring muscle activity for anterior cruciate ligament-reconstructed (ACLR) and control participants, mean $\pm$ SD. ACLR subjects demonstrated significantly less quadriceps activity than control subjects regardless of fatigue state (* $P=.010$).

Table 1

Participant Demographics (Mean $\pm$ SD)

Group	Participants	Sex	Age (yrs)	Height (m)	Mass (kg)	Time from ACL injury to ACLr (days)	Time to Test post-ACLR (days)	Graft Type (PT, STG)	Grade I Collateral Ligament Injury (MCL, LCL, both)	Debridement of Meniscus
ACLR	N=12	7m/5f	22.08 $\pm$ 4.7	1.8 $\pm$ 0.1	77.7 $\pm$ 11.9	75.1 $\pm$ 54.9	248 $\pm$ 54.6	PT =7 STG = 5	MCL=4 LCL=1 both=1	Lateral=2 Medial=0 both=1
Control	N=13	4m/9f	22.9 $\pm$ 4.3	1.7 $\pm$ 0.1	66.9 $\pm$ 9.8	NA	NA	NA	NA	NA

Abbreviations: LCL, lateral collateral ligament; MCL, medial collateral ligament; NA, not applicable; PT, patellar tendon; STG, semitendinosus/gracilis

Table 2
Main Outcome Measures Standardized Effect Size Interpretations (Effect size [95% Confidence Interval])

Measure	Pre-Fatigue	Post-Fatigue
Quadriceps:Hamstring CCI	0.04 (-0.74, 0.83) <i>weak</i>	0.45 (-0.34, 1.24) <i>small</i>
Quadriceps Activity	-1.29 (-2.15, -0.43) <i>strong</i>	-0.69 (-1.50, 0.12) <i>moderate</i>
Hamstring Activity	0.63 (-0.17, 1.43) <i>moderate</i>	0.71 (-0.10, 1.52) <i>moderate</i>

Abbreviations: CCI, co-contraction index

Table 3

ACLR Muscle Activity by Graft Type (Mean $\pm$ SD)

Graft Type	Pre-Fatigue			Post-Fatigue		
	Quadriceps	Hamstring	CCI	Quadriceps	Hamstring	CCI
PT (N=7)	43.82 $\pm$ 9.27	0.40 $\pm$ 0.13	0.45 $\pm$ 0.12	23.73 $\pm$ 16.66	0.23 $\pm$ 0.17	0.25 $\pm$ 0.16
STG (N=5)	48.01 $\pm$ 5.40	0.43 $\pm$ 0.08	0.38 $\pm$ 0.10	27.13 $\pm$ 11.39	0.24 $\pm$ 0.13	0.20 $\pm$ 0.05

Abbreviations: CCI, co-contraction index; PT, patellar tendon; STG, semitendinosus/gracilis