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Effects of ACL reconstruction surgery on muscle activity of the lower limb during a jump-cut maneuver in males and females

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Abstract

We compared muscle activity of the quadriceps, hamstring, and gastrocnemius muscles when ACL-intact (ACL_{INT}) and ACL-reconstructed (ACL_{REC}) male and female subjects performed a jump-cut task. Surface electromyography sensors were used to evaluate time to peak muscle activity and muscle activity ratios. Rectus femoris (RF) and vastus medialis (VM) peak timing was 71 ms and 78 ms earlier in ACL_{INT} than in ACL_{REC} subjects, respectively. Biceps femoris (BF) peak timing was 90 ms earlier in ACL_{INT} than in ACL_{REC} subjects and 75 ms earlier in females than in males. Medial gastrocnemius (MG) muscle peak timing was 77 ms earlier in ACL_{INT} than in ACL_{REC} subjects. Lateral gastrocnemius (LG) and MG muscle peak times were 106 ms and 87 ms earlier in females than in males, respectively. The RF, VM, BF and MG peaked later in ACL_{REC} than in ACL_{INT} subjects. There was evidence suggesting that the loading phase quadriceps:hamstring (quad:ham) muscle activity ratio was greater in ACL_{REC} than in ACL_{INT} subjects. Finally, the injury risk phase quad:ham muscle activity ratio was found to be 4.8 times greater in females than in males. In conclusion, there are differences in muscle activity related to ACL status and sex that could potentially help explain graft failure risk and the sex bias.

Keywords

ACL; Injury; Reconstruction; Muscle; EMG

INTRODUCTION

Injuries to the anterior cruciate ligament (ACL) are very common and risk to injury is greatest in sports that involve jump-cut maneuvers without contact from another player. Non-contact ACL injuries, which occur during the first 40 ms after the lower limb decelerates at ground contact, are two to ten times more frequent in female compared to male athletes.^{1,2,3} Unfortunately, the ACL does not readily heal,⁴ and in many cases requires surgical reconstruction to stabilize the knee.⁵ The removal of the native ACL and its replacement with a tendon graft likely results in a neurologic sensory deficit which may place patients following ACL reconstruction surgery at higher risk for tearing the ACL graft.^{6,7} It is believed that the alterations in muscle activity of the quadriceps muscles, hamstring muscles, and both heads of the gastrocnemius muscle are factors contributing to

injury risk,^{8,9} the observed sex injury disparity,^{9,10} and the risk of re-injury following surgery.¹¹ Furthermore, some, though not all, neuromuscular training programs have been shown to reduce the risk of ACL injury.^{12,13} To further understand mechanisms of ACL injury it is necessary to explore the individual and combined functions of these muscles during activities associated with non-contact ACL injury in both ACL-intact (ACL_{INT}) and ACL-reconstructed (ACL_{REC}) subjects and female (F) and male (M) subjects.

Past studies have shown that females display greater quad:ham muscle activity ratios, implying that hamstring muscle activity does not increase to compensate for increased quadriceps muscle activity in females.¹⁴ Since the hamstring muscles work to unload the ACL by pulling the tibia posterior and the quadriceps muscles load the ACL by shifting the tibia anterior, greater activation of the quadriceps muscles in relation to the hamstring muscles could play a role in the increased frequency of ACL injury in females.¹⁵ The activity of individual quadriceps and hamstring muscles has also been compared between men and women. For example, the BF has been shown to reach peak muscle activity earlier in women than in men.¹⁶ We chose to look at time to peak muscle activity because these values can provide insight into the muscle response after landing, which may correlate to its function at stabilizing the knee during the maneuver. While sex differences have been widely studied, the impact of ACL reconstruction status on muscle activity has not been evaluated to the same extent. Studies questioning why ACL_{REC} subjects are more susceptible to future injury suggest that a sensory deficit in the reconstructed knee may be responsible for ipsilateral and possibly contralateral injuries.¹⁷

The purpose of this study was to compare the timing and activity levels of the quadriceps, hamstring, and gastrocnemius muscles when ACL_{INT} and ACL_{REC} male and female subjects performed a jump-cut maneuver, an activity known to place the ACL at risk for injury.^{18,19} The primary outcome measures included the time to peak activity and the quad:ham and gastrocnemius:hamstring (gastroc:ham) muscle activity ratios, which were evaluated from 50 ms before contact to maximum knee flexion, with an emphasis on the first 40 ms following ground contact, when the risk of ACL injury is highest. We hypothesized that differences in all of these outcomes would be observed between ACL status (ACL_{INT} vs. ACL_{REC}) and sex (M vs. F).

METHODS

Subjects

All subjects granted their informed consent following Institutional Review Board approval. Ten ACL_{INT} subjects (5 females ages 24.6±2.3 years; 5 males ages 25.8±4.2 years) and ten ACL_{REC} subjects (6 females ages 24.7±6.7 years; 4 males ages 29.3±6.1 years) were enrolled (Table 1). The subjects were part of another study evaluating differences in knee kinematics during the jump-cut maneuver.^{20,21} Of the ten ACL_{REC} subjects, seven were reconstructed using bone-patellar tendon-bone autografts and three using hamstring tendon autografts. The inclusion criteria for the ACL_{INT} subjects were: 1) no history of lower extremity injury; 2) no neurological disease(s); 3) no pregnancy; and 4) a Tegner activity score of five or greater.²² The inclusion criteria for the ACL_{REC} patients were: 1) unilateral ACL reconstruction using bone-patellar tendon-bone or four-stranded hamstring tendon autograft (looped semitendinosus and gracilis); 2) greater than five years post ACL reconstruction; 3) no systemic infections; 4) no neurological disease(s); 5) no pregnancy; and 6) a Tegner activity score of five or greater.²²

One leg was chosen at random (6 left and 4 right) for the ACL_{INT} subjects, and the reconstructed leg was evaluated (7 left and 3 right) for the ACL_{REC} subjects. The selected leg was outfitted with 23 retro-reflective surface markers, which allowed measurement of

foot, shank and thigh motion using optical motion capture (OMC). The marker set to compute knee kinematics from OMC was based on that of Buczek, et al.²³

Each leg was outfitted with six bipolar electromyography (EMG) electrodes (Myomonitor IV, Delsys Inc., Boston, MA). The skin surfaces were prepped by shaving, abrading, and then cleaning with alcohol prep pads. The surface electrodes were then applied using specially designed adhesive strips to two muscles within the quadriceps group [rectus femoris (RF) and vastus medialis (VM)], two muscles within the hamstrings group [semitendinosus (ST) and biceps femoris (BF)], and the two heads of the gastrocnemius muscle [medial (MG) and lateral (LG)]. The electrode placement was performed according to standardized surface electrode placement procedures.^{16,24,25}

Jump-Cut Maneuver

Subjects were asked to perform a jump-cut maneuver, also studied by Ford, et al. and Miranda, et al., to recreate an activity associated with non-contact ACL injury (Fig. 1).^{18,20,21,25,26} Subjects stood with their knees bent at a 45° flexion angle approximately one meter from a target placed on a force plate (Kistler model 9281B, Amherst, NY, USA). The subject was cued by a verbal prompt to jump toward the landing target at the center of the force plate. A visual directional cue then instructed the subject to sidestep cut through a target placed two meters away from the landing target at a 45° angle to either the right (R) or left (L). The subject then jogged beyond the target. The subject performed 10 trials, unaware of what the directional cue would be each time, and data were recorded only during the trials where the subject landed and cut with the outfitted leg. Data were collected for the reconstructed leg of ACL_{REC} and for a leg chosen at random of ACL_{INT} subjects. Incorrectly executed trials, such as cutting in the wrong direction, were excluded. Two subjects were excluded because of technical errors with the surface electrodes.

Data Collection and Processing

The jump-cut maneuver was performed and ground reaction force (GRF), kinematic, and EMG data were collected in the W.M. Keck Foundation XROMM Facility at Brown University (Providence, RI, USA; <http://www.xromm.org>).²⁷ GRF data were measured at a sampling frequency of 5,000 Hz. EMG data were recorded for the RF, VM, ST, BF, MG and LG using the Myomonitor IV Wireless EMG System and Single Differential Detection surface EMG sensors at a sampling frequency of 5,000 Hz. Kinematic data were collected using optical motion capture (Qualisys Oqus 5, Gothenburg, Sweden) at a sampling frequency of 250 Hz. All modalities were time synchronized.

All EMG signals were pre-processed according to manufacturer recommendations. Signals were full-wave rectified, high-pass filtered at 20 Hz and low-pass filtered at 500 Hz.²⁸ Filtered signals were smoothed by calculating the root mean square (RMS) value within a 500-frame moving window (Fig. 2).²⁹ All signals were processed using Visual3D (C-Motion, Germantown, MD, USA).

Data Analysis

Muscle peak times were determined by finding the global maximum of the processed, smoothed signals (Fig. 3). The signals for each muscle were integrated over the preparatory phase (PREP; 50 ms before contact to contact), the loading phase (LOAD; contact to maximum knee flexion), and a subdivision of the loading phase called the injury risk phase (RISK; first 40 ms of LOAD phase) to obtain a descriptive parameter (area under the curve; AUC) for each muscle during all phases (Fig. 3).¹⁴ The time of contact was determined using the GRF data obtained from the force plate (Fig. 3).²⁰ The AUC parameters were used to calculate ratios of quad:ham and gastroc:ham muscle activity for each trial during all

phases. The quadriceps, hamstring, and gastrocnemius ratio parameters were determined for each trial by summing the AUC for the quadriceps (RF+VM), gastrocnemius (MG+LG), or hamstring (ST+BF) muscles. These ratios were ensemble averaged across all trials for each subject during all phases.

Outcome measures were compared between ACL reconstruction status (ACL_{INT} vs. ACL_{REC}) and sex (M vs. F) using two-way analyses of variance. The Holm-Sidak method was used to make pair-wise multiple comparisons when significant ACL reconstruction status and sex interactions were determined. The study was designed to have power = 0.80 using $\alpha = .05$ to detect main effects corresponding to a Cohen's $f = 0.62$.³⁰ This is equivalent to a $\eta^2 = .30$, which can be interpreted as a specific factor (i.e. ACL_{INT}/ACL_{REC} or male/female) explaining approximately 30% of the total variance.

RESULTS

Muscle Peak

We observed RF and VM peak timing to be 71 ms and 78 ms earlier in ACL_{INT} subjects than in ACL_{REC} subjects, respectively (RF: $p = 0.036$; VM: $p = 0.026$) (Fig. 4). No significant differences in RF and VM peak timing were observed between males and females ($p > 0.496$). We also found BF peak timing to be 90 ms earlier in ACL_{INT} subjects than in ACL_{REC} subjects ($p = 0.014$) and 75 ms earlier in females than in males ($p = 0.035$). ST peak timing was not significantly different between males and females or between ACL_{INT} and ACL_{REC} subjects ($p > 0.154$). We found that MG peak timing was 77 ms earlier in ACL_{INT} subjects than in ACL_{REC} subjects (MG: $p = 0.020$). LG peak timing was not significantly different between ACL_{REC} and ACL_{INT} subjects ($p > 0.114$). Finally, LG and MG peak times were observed to be 106 ms and 87 ms earlier in females than in males, respectively (LG: $p = 0.012$; MG: $p = 0.010$).

Muscle Activity

No significant differences were observed between the PREP phase quad:ham activity ratios of ACL_{INT} and ACL_{REC} subjects or between those of males and females ($p > 0.139$). A significant difference was not found between the RISK phase quad:ham ratios of ACL_{INT} and ACL_{REC} subjects ($p > 0.161$). The RISK phase quad:ham activity ratio was found to be 4.8 times greater in females than in males ($p = 0.049$). The LOAD phase quad:ham activity ratio was observed to be 2.8 times greater in ACL_{REC} subjects than in ACL_{INT} subjects ($p = 0.059$). The LOAD phase quad:ham ratios in males and females were not significantly different ($p > 0.116$) (Fig. 4). The PREP phase gastroc:ham activity ratios in ACL_{INT} and ACL_{REC} subjects and in males and females were not observed to be significantly different ($p > 0.395$). The RISK phase gastroc:ham activity ratios in ACL_{INT} and ACL_{REC} subjects and in males and females were not significantly different ($p > 0.299$). The LOAD phase gastroc:ham activity ratios in ACL_{INT} and ACL_{REC} subjects and in males and females were not significantly different ($p > 0.294$).

DISCUSSION

We measured the quadriceps, hamstring, and gastrocnemius muscle activity in ACL_{INT} and ACL_{REC} male and female athletes during a jump-cut maneuver associated with non-contact ACL injury. Our results indicate that the RF, VM, BF and MG in ACL_{REC} subjects peak later after contact than those in ACL_{INT} subjects. A sensory deficit in the ACL_{REC} knees could potentially explain these delayed peak times. While many studies have compared quad:ham muscle activity ratios between sexes, a comparison of these ratios between ACL_{REC} and ACL_{INT} subjects has not been performed. While not significant, there was a

strong trend ($p=0.059$) suggesting that the LOAD phase quad:ham muscle activity ratio is greater in ACL_{REC} subjects than ACL_{INT} subjects. This result suggests ACL_{REC} subjects have a greater amount of quadriceps activity in relation to hamstring activity compared to ACL_{INT} subjects during the LOAD phase.

Our results revealed that components of quadriceps, hamstring and gastrocnemius muscles peaked later after contact in ACL_{REC} than in ACL_{INT} subjects. Other researchers report that ACL_{REC} subjects display sensory deficits in the reconstructed knee. Such sensory deficit is thought to be due to impaired proprioception,¹⁷ or more specifically due to damaged ACL mechanoreceptors.³¹ When taken together, these studies indicate the delayed peak time of quadriceps, hamstring and gastrocnemius muscles in ACL_{REC} subjects.

Our results also showed that the LOAD phase quad:ham ratio was greater in ACL_{REC} than in ACL_{INT} subjects. While, to our knowledge, no previous studies have compared muscle activity ratios between ACL_{INT} and ACL_{REC} subjects, comparisons between sexes can be made. Hanson et al. performed a similar study on muscle activation in male and female athletes during side-step cutting maneuvers.¹⁴ The authors found that females demonstrated greater quad:ham coactivation ratios than males. They explained that quad:ham coactivation stabilizes the knee joint by increasing joint stiffness, thereby reducing the strain on the ACL. Consequently, an uneven coactivation ratio will not provide for as much stability, and thus will make one more susceptible to injury of the ACL due to increased ACL strain. The authors concluded that females use a quadriceps muscle-dominant activation pattern during the maneuver, and that this is a risk factor for ACL injury. This conclusion is supported by the kinematic data that was collected as part of a related study, which revealed that anterior tibial translation increased at a faster rate in females and that females displayed less overall knee flexion. These results suggest that increased quadriceps activity may keep the knee more extended, resulting in an increased rate of anterior tibial translation and thus susceptibility to injury.²¹ It is possible that ACL_{REC} subjects utilize the same quadriceps-dominant activation pattern. Therefore, this could provide an explanation for the observed re-tear rate in ACL_{REC} subjects.^{11,32} Further studies could explore the mechanism behind the increased quadriceps muscle activity in ACL_{REC} subjects.

The differences observed between sexes suggest the BF peaks earlier in females than in males. As part of the hamstring muscle group, the earlier peak in BF muscle activity may provide an explanation as to why females tend to display greater quad:ham muscle activity ratios and thus lower hamstring activity in comparison to quadriceps activity. If the BF is peaking earlier after contact in females, the LOAD quad:ham ratio may be largely comprised of decreasing BF muscle activity. This, combined with a later peak in quadriceps activity, may create the observed imbalance in quad:ham ratio after contact. Conversely, the later BF peak time in males may lead to the ratio taking into account less of the decreasing BF activity after peak activity is reached. Consequently, this may further explain the higher frequency of ACL injury in female athletes. Our results also show that the gastrocnemius muscles (MG & LG) peaked earlier in females than in males. Considering the sex-bias of ACL injury and the fact that the gastrocnemius is an ACL antagonist (i.e., strains the ACL),³³ the earlier peak time of the gastrocnemius muscles may place more strain on the female ACL, increasing its susceptibility to injury. The earlier peak times of several muscles in female compared to male athletes are perhaps due to dissimilarities in muscle strength, training regimens, and/or anatomy.

In a similar study performed by Beaulieu, et al.,¹⁶ EMG data were used to examine muscle activity in male and female subjects during an unanticipated cutting maneuver. They found, as we did, that the BF, a hamstring muscle, in females reached peak muscle activity earlier than that in males. The authors suggested that as a result of this earlier peak time, females

experience decreasing hamstring muscle activity as ACL strain is increasing and reaching its peak. Since the male BF is peaking later, males experience increased hamstring muscle activity closer in time to peak ACL strain. Cowling and Steele found the same result and suggested that the better synchrony between peak hamstring activity and peak ACL strain in males provides for enhanced stability and protection of the ACL.³⁴ This is a valid conclusion since hamstring muscles are known to act as an agonist to the ACL, as they counterbalance the strains produced on the ACL by the quadriceps and gastrocnemius muscles. Our results support these studies and provide a possible explanation for increased ACL injury in females. If the hamstring muscles in females peak too early, then perhaps the role these muscles play in decreasing ACL strain cannot be fulfilled to the same extent as in males, whose hamstring muscles peak later and thus closer in time to peak ACL strain. If there is decreased hamstring muscle activity when ACL strain is at its highest, it makes sense that ACL injury would occur more easily and frequently.

We also found that the RISK phase quad:ham ratio was significantly greater in females than in males. The RISK phase encompasses the first 40 ms after contact and is an important time period to examine because peak ACL load has been shown to occur approximately 40 ms after ground contact.³ As a result, by looking at the muscle activity ratios during this phase, we can determine how the different muscles are firing when ACL injury risk is highest. Our finding that the RISK phase quad:ham ratio was nearly 5 times greater in females than in males supports the conclusion that females utilize a quadriceps-dominant activation pattern upon landing. Since the quadriceps muscles strain the ACL and since they are firing to a much greater degree than the hamstring muscles, which reduce strain on the ACL, one can conclude that the risk of ACL injury is greater in females during this time period. The RISK phase quad:ham ratio in males was found to be closer to unity, thus showing that males utilize the quadriceps and hamstring muscles to a more similar degree thereby not straining the ACL as much as females.

The potential for the gastroc:ham muscle activity ratio as a risk factor of ACL injury has not been previously explored. Activation of the gastrocnemius is known to strain the ACL,³³ and thus could potentially play a role in non-contact ACL injury. While our results were not significant, the mean gastroc:ham ratio was higher in ACL_{INT} subjects compared to ACL_{REC} subjects and higher in males compared to females. These results suggest that further research could be done with a focus on the interaction between the hamstring and gastrocnemius muscles.

One limitation of this study is that no MVC data were recorded, so we were unable to look at the relative magnitudes of each muscle. While this was a limitation, numerous previous studies have used MVC data; therefore, our study presented a different data set than what was already available. Another limitation is that we used surface electrodes to obtain the EMG signals instead of more precise fine wire electrodes. This is only a minor limitation, however, because a previous study directly compared surface and fine wire electrodes and concluded that the two types of electrodes produce highly similar results and show similar variability.³⁵ We also did not look at all individual components of the quadriceps, hamstring, and gastrocnemius muscle groups. However, our results still showed trends within muscle groups providing justification for a similar study on the excluded muscles. Additionally, no data were collected on the motion of the uninvolved leg during the jump-cut maneuver. These data were not collected because this study was part of a larger study involving radiographic exposure, which we needed to limit;²¹ however, a future study could be performed to examine the motion of both legs during a similar maneuver. Another limitation is that all of our analyses were performed relative to ground contact. We chose contact as our reference time because our field of view was restricted by the biplanar videoradiographic system we used to measure kinematics in our related study²¹.

Consequently, we focused our attention on the landing-cut portion of the study where the ACL has been shown to be at greatest risk. A final limitation is the relatively small sample size that was sufficient to detect relatively large magnitude effects. Despite the limited sample size, we were able to document meaningful differences in muscle response.

The results of our study support the hypothesis that differences would be observed as a function of ACL reconstruction status and sex for the quadriceps, hamstring, and gastrocnemius muscles during a jump-unanticipated cut maneuver. Specifically, we observed later peak timing in the RF, VM, BF and MG of ACL_{REC} subjects compared to ACL_{INT} subjects. Moreover, we found that the hamstring and quadriceps muscles peaked earlier in females than in males. We also saw that the quad:ham muscle activity ratio during the LOAD phase was greater in ACL_{REC} subjects than in ACL_{INT} subjects. Finally, we found that the RISK phase quad:ham muscle activity ratio was significantly greater in females than in males.

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Fig. 1.

Illustration showing the experimental set up used during this experiment. The subject is pictured performing the jump-cut maneuver. When the subject lands on the force plate they cut and push off to the left (L) or right (R) based on the directional prompt (arrow) directly in front (not shown). A selection of the OMC markers (open circles) and EMG electrodes (black squares) are shown on the subject's right leg. The EMG electrodes were plugged into the wireless data collection device attached to each subject's waist.

Fig. 2.

Processed, smoothed EMG traces for the RF, VM, ST, BF, LG and MG over the entire length of the activity. The solid and dotted lines represent the time of landing contact and the time of max flexion, respectively.

Fig. 3.

(A) Sample processed, smoothed EMG trace for the RF. (B) Trace of the flexion angle of the knee during the jump-cut maneuver. (C) Trace of the ground reaction force during the jump-cut maneuver. For (A), (B), and (C): Assorted dotted and solid lines show the times of: contact, max flexion, and muscle peak. The shaded regions denote the preparatory phase, the loading phase, and the injury risk phase, which encompassed the first 40 ms of the loading phase.

Fig. 4.

(A) Bar graph showing the mean peak times for all 6 muscles studied. (B) Bar graph showing the PREP, LOAD, and RISK quad:ham (Q:H) and gastroc:ham (G:H) muscle activity ratios. For (A) and (B): Dotted and solid lines above the bars display p-values for differences between reconstruction status (ACL_{INT} vs. ACL_{REC}) or sex (M vs. F) that were either significant or close to being significant.

Table 1

shows the age, weight (in kilograms), height (in centimeters), sex, and reconstruction status of all subjects involved in the study.

SEX	AGE	CONDITION	HEIGHT (centimeters)	WEIGHT (kilograms)
Female	25	Intact	173	69
Female	25	Intact	172	63
Female	28	Intact	170	68
Female	22	Intact	164	65
Female	23	Intact	163	61
Male	22	Intact	186	77
Male	33	Intact	166	80
Male	25	Intact	180	92
Male	25	Intact	177	85
Male	24	Intact	179	73
Female	20	Reconstructed	176	62
Female	38	Reconstructed	160	84
Female	22	Reconstructed	164	55
Female	22	Reconstructed	178	66
Female	21	Reconstructed	163	75
Female	25	Reconstructed	166	65
Male	32	Reconstructed	179	78
Male	27	Reconstructed	172	90
Male	36	Reconstructed	189	79
Male	22	Reconstructed	180	107