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Muscle Preactivity of Anterior Cruciate Ligament-Deficient and -Reconstructed Females During Functional Activities

Richard G. DeMont, MS, CAT(C); Scott M. Lephart, PhD, ATC; Jorge L. Giraldo, MD; C. Buz Swanik, PhD, ATC; Freddie H. Fu, MD

Neuromuscular and Sports Medicine Research Laboratory, Musculoskeletal Research Center, Department of Orthopaedic Surgery, University of Pittsburgh, Pittsburgh, PA

Objective: Underlying the ability of the hamstrings to decrease tibial anterior shear is the time of firing in comparison with the quadriceps. This timing may be aided by neural programming during a planned or expected activity. It is theorized that individuals who have better programming ability will suffer fewer anterior cruciate ligament (ACL) injuries due to joint protection through muscular stabilization. A component of this dynamic restraint is the development of muscular tension before the knee is loaded. The objective of our study was to compare the muscular activity before footstrike in ACL-deficient (ACL-D), ACL-reconstructed (ACL-R), and control (C) females during functional activities.

Design and Setting: Active females were divided into groups based on their ACL status. The study was conducted in a neuromuscular research laboratory.

Subjects: Twenty-four female subjects (ACL-D = 6, ACL-R = 12, C = 6).

Measurements: Integrated electromyographic (IEMG) activity from the thigh (vastus medialis obliquus [VMO], vastus lateralis [VL], medial hamstring, and lateral hamstring) and leg (medial gastrocnemius and lateral gastrocnemius [LG]) and footswitch signals were recorded during downhill walking (15° at 0.92 m/s), running (2.08 m/s), hopping, and landing from a step (20.3 cm). IEMG activity was normalized to the mean amplitude of the sample and analyzed for area and mean amplitude for 150 milliseconds before heelstrike. Side-to-side differences were determined by *t* tests, and separate one-way analyses of variance (ANOVA) were used to detect differences among the 3 groups for each muscle of each activity.

Results: IEMG area side-to-side differences for the ACL-D group appeared in the LG (involved [I] = 36.4 ± 19.7, uninvolved [U] = 60.1 ± 23.6) during landing, in the VMO (I = 11.4 ± 3.8, U = 7.2 ± 3.1) and VL (I = 13.3 ± 2.7, U = 8.9 ± 1.9) during running, and in the VMO (I = 9.2 ± 4.2, U = 19.5 ± 7.3) during downhill walking. IEMG mean amplitude side-to-side differences for the ACL-D group appeared in the LG (I = 79.7 ± 30.3, U = 122.3 ± 34.9) during downhill walking and in the VMO (I = 78.6 ± 23.2, U = 45.8 ± 18.9) during the run; IEMG mean amplitude side-to-side differences for the ACL-R group appeared in the LG (I = 74.7 ± 40.0, U = 52.8 ± 14.3) during the hop. The ACL-D group had higher IEMG means than control in the VL (ACL-D = 12.9 ± 5.8, C = 7.1 ± 3.9), but lower in the VMO (ACL-D = 9.2 ± 4.2, C = 15.7 ± 3.6).

Conclusions: The side-to-side differences of the ACL-D and ACL-R groups, as well as the group differences between ACL-D and control, suggest that different muscle activation strategies are used by females when performing different dynamic activities. Therefore, muscle unit differentiation may be the cause of our results. These changes appear to be reversed through surgery or the associated postoperative rehabilitation.

Key Words: closed kinetic chain, preparation, muscle, activation

Recent interest in the higher incidence among females of anterior cruciate ligament (ACL) injury has prompted numerous studies surrounding potential causes. Arendt and Dick[1] found the rate of ACL injury in females to be considerably more than that of males. Malone et al[2] found the ACL injury incidence rate to be 8 times higher for females compared with males. Considering that 78% of these injuries are the result of noncontact mechanisms,[3] attention has been placed on the neuromuscular control abilities of females who are ACL deficient (ACL-D) or reconstructed (ACL-R) and compared with their male cohorts.[4,5]

Typically, males and females play the same sports at the same intensity levels. The court dimensions and area of the floor surface do not change, and only recently have shoes been designed for females. Putting aside the anatomical issues such as Q-angle, notch size, and ligament size, which are to date inconclusive,[6–8] the ability to prevent anterior tibial shear by controlling knee position with dynamic activity is of interest.

It has been suggested that hamstring muscle activity decreases stress on the ACL at all joint positions.[9] Muscle activation also increases the stiffness of the knee.[10] It is

Address correspondence to Richard G. DeMont, MS, CAT(C), Concordia University, Department of Exercise Science, 7141 Sherbrooke St. West, Montreal, PQ, Canada H4B 1R6. E-mail address: rdemont@alcor.concordia.ca

unclear, however, whether the timing of the hamstring contraction in comparison with the quadriceps contraction is the crucial element in preventing injury. The hamstring may not be strong enough to overcome stress on the ACL,[10,11] yet greater hamstring electromyographic (EMG) activity is present in ACL-D individuals, who have a greater need to prevent anterior tibial translation (ATT) than individuals with healthy knees. The changes associated with ACL-D are decreased rectus femoris and vastus lateralis (VL) EMG activity, paired with increased biceps femoris EMG activity, compared with normal subjects.[12,13] Many of these studies reported data that were collected during and separated by the portions of the gait cycle[12,14–18] or reported for the length of the stance phase.[13,19]

Proprioception, both position sense and kinesthesia, is enhanced in athletes,[20] diminished in ACL-D individuals,[21] and improved with reconstruction.[19,20] If the changes in proprioceptive abilities are linked to neural programming during a planned or expected activity, the muscular stabilization that is required before loading of the knee to prevent injury might be compromised. Our interest was in examining the muscle activity before landing. Our purpose was to compare the muscular activity before footstrike in ACL-D, ACL-R, and control (C) individuals during dynamic activities.

METHODS

Subjects

Twenty-four female subjects were grouped according to the status of their ACLs: 6 subjects were in the ACL-D group, 12 were in the ACL-R group, and 6 were assigned to a control group. The subjects in the control group were healthy and had no history of knee pathology. The subjects' average age was 29.4 ± 10.4 years, height was 168.4 ± 10.7 cm, and weight was 61.2 ± 6 kg. All subjects in the ACL-D and ACL-R groups had completed their rehabilitation programs associated with their injuries and had returned to sporting activity. The minimum time from surgery (ACL-R) or injury (ACL-D) was 6 months. The ACL-D and ACL-R groups were rated equally in activity level, as the combined value for the Tegner Activity Score[22] was 6.8 ± 1.5 and the combined value on the Lysholm Knee Scoring Scale[23] was 92.9 ± 5.4. Institutional review board approval was granted at the University of Pittsburgh before the study began, and each subject gave informed consent before data collection.

Functional Activities

Four activities were used to generate dynamic muscle activity in the lower extremity. Downhill walking on a treadmill with a 15° decline at 0.92 m/s was continued for 15 to 20 steps to ensure that enough steps of a clear footswitch signal were available to determine heel contact. Running, which was completed at 2.08 m/s on a level treadmill, followed the same criteria regarding number of steps and footswitch-monitoring procedure. Hopping 10 steps was subject controlled for height and pace and was performed on the floor for approximately 15 meters, again to ensure adequate samples. Hopping strategies were not discussed except to ensure safety and adequate footswitch signals. To perform the landing task, subjects jumped from a 20.3-cm step and landed balanced on one leg. Performance strategies were not discussed for the landing task except to instruct the subject to land softly in order to avoid injury. All tasks were repeated because data could be collected only from one leg at one time. The testing order was as follows: downhill walking, running, hopping, and landing.

EMG Collection

Skin preparation for the EMG electrodes was carried out for all subjects. Each electrode placement point was cleaned with isopropyl alcohol and abraded with an emery board. Any visible hair was removed. This preparation was completed to improve application of the electrodes and reduce the acceptable impedance to below 2 kΩ.

EMG activity was measured from the vastus medialis oblique (VMO), VL, medial hamstring, and lateral hamstring in each thigh and the medial gastrocnemius and lateral gastrocnemius (LG) in each leg. Electrode placement for the VMO bisected the muscle in an anteroposterior division and was at a point distal from the motor point of the muscle halfway to the insertion with the quadriceps tendon. The VL electrode point was halfway between the iliac crest and quadriceps insertion and halfway from the medial border with the vastus intermedialis and the anterior edge of the iliotibial band of fascia. The medial hamstring electrodes were placed over the muscle belly halfway between the ischial tuberosity and the tibial insertion point, at least 5 cm proximal to the musculotendinous junction. The lateral hamstring electrodes were placed over the biceps femoris muscle halfway between the ischial tuberosity and the fibular insertion site, at least 5 cm proximal to the musculotendinous junction. The medial gastrocnemius electrodes were placed centrally in a mediolateral fashion and distal from the midpoint of the belly to the tendinous junction. The LG electrodes were placed in a similar fashion and similar orientation to those of the medial gastrocnemius, except that placement was slightly higher due to the more proximal orientation of the muscle. Two footswitches were placed on the plantar surface of the foot to indicate heel contact and toe-off point of the gait cycle.

Processing

The EMG signal was collected via a telemetry EMG system (Noraxon Telemyo, Noraxon, Scottsdale, AZ) through integration with a computer equipped with collection and analysis software (MyoResearch97, Noraxon, Scottsdale, AZ). The Telemyo system sampled the muscle activity at 1000 Hz with a common mode rejection ratio of 130 db and bandpass filtered (Butterworth) the signal at 15 Hz (low) and 500 Hz (high). The signal was amplified (gain 500) and transferred using an 8-channel FM transmitter to a receiver, where it was further amplified (gain 500, total gain 1000). The signal was then digitized by an analog-to-digital converter (Keithley DAS-1000, Keithley Instruments, Inc, Taunton, MA), integrated, and stored using the MyoResearch97 software before further processing. The integrated EMG (IEMG) signal was normalized to the mean amplitude of the ensemble average[24] of 5 gait cycles. The 5 cycles were identified by manually inserting markers that coincided with the foot contact signal (Figure 1). We recorded area and mean amplitude for 150 milliseconds before footstrike for statistical analysis.

Statistical Analysis

Differences between involved and uninvolved sides were determined by paired *t* tests on the mean amplitude and area of the EMG signal for each muscle during each activity. A one-way analysis of variance (ANOVA) was used to determine if there was a difference among the three groups for each muscle during each activity. Tukey post hoc analysis was completed, when indicated, to determine differences between the levels of the group variable. The level of statistical significance was set at $P = .05$.

RESULTS

Because of the normalization process used to compare the EMG signals, each value is reported as a percentage of the mean. For area IEMG, the *t* test revealed side-to-side differences between the LG (involved [I] = 36.4% ± 19.7%, uninvolved [U] = 60.1% ± 23.6%, $t_5 = 2.35$, $P < .05$) of the ACL-D group during the landing activity. The ACL-D group also exhibited differences in the VMO (I = 11.4% ± 3.8%, U = 7.2% ± 3.1%, $t_5 = 2.08$, $P < .05$) and VL (I = 13.3% ± 2.7%, U = 8.9% ± 1.9%, $t_5 = 2.85$, $P < .05$) during running and the VMO (I = 9.2% ± 4.2%, U = 19.5% ± 7.3%, $t_5 = 2.03$, $P < .05$) during downhill walking (Figure 2).

For mean amplitude of the IEMG, the ACL-D was different in the LG (I = 79.7% ± 30.3%, U = 122.3% ± 34.9%, $t_5 = 4.14$, $P < .05$) during downhill walking and VMO (I = 78.6% ± 23.2%, U = 45.8% ± 18.9%, $t_5 = 2.94$, $P < .05$) during the run. The ACL-R group exhibited a side-to-side difference when compared for mean amplitude of the IEMG on LG (I = 74.7% ± 40.0%, U = 52.8% ± 14.3%, $t_{11} = 2.03$, $P < .05$) during the hop (Figure 3).

The ANOVA revealed group differences on the involved VL during the hop and VMO when walking downhill. The ACL-D had significantly higher IEMG area than the control group in VL (ACL-D = 12.9% ± 5.8%, C = 7.1% ± 3.9%, $F_{2,23} = 4.19$, $P < .05$), but lower in VMO (ACL-D = 9.2% ± 4.2%, C = 15.7% ± 3.6%, ($F_{2,23} = 4.04$, $P < .05$). No other measures of muscle activity exhibited significant differences bilaterally or between groups (Figure 4).

DISCUSSION

During running, the ACL-D group exhibited increases in VMO and VL activity. The rehabilitation programs could account for this increase through the increased demand placed on the injured side. Frequently, individuals will exercise the injured side harder or with more concentration because they fail to respect the need to train bilaterally, and the injured side is the focus of the health care professionals who help them manage the injury. The lack of hamstring changes and the activity-dependent gastrocnemii differences in our study led us to another explanation. The increased signal could be the electrical response needed to generate muscle balance ratio during a given task. In this scenario, the higher activity is an attempt to increase the output of a weaker muscle. The likely explanation for the VMO decrease during the downhill activity is the attempt by the neuromuscular system to counteract or

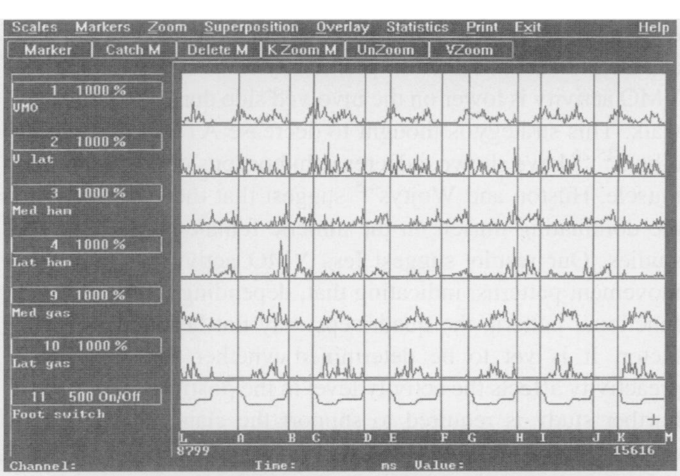

Figure 1. EMG screen showing vertical markers that identify stance (A-B, C-D) and swing (B-C, D-E) phases of gait. The ensemble average is taken from the mean of 5 cycles.

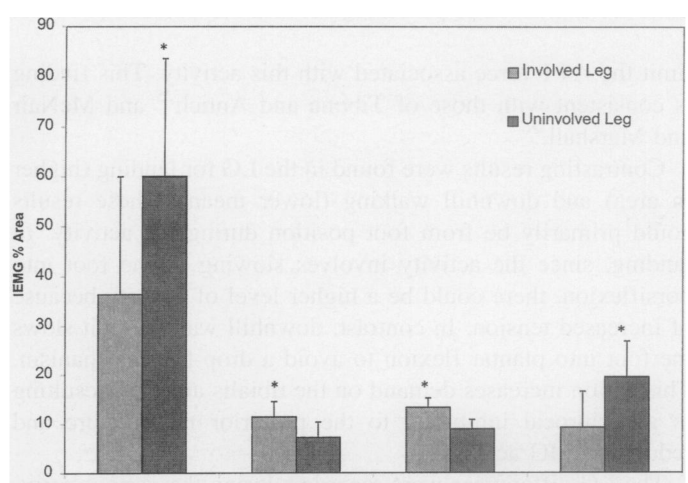

Figure 2. Significant side differences for IEMG area of LG, VMO, and VL during specific activities. Units are expressed as percentage of mean amplitude. DH, downhill walk; *, $P < .05$

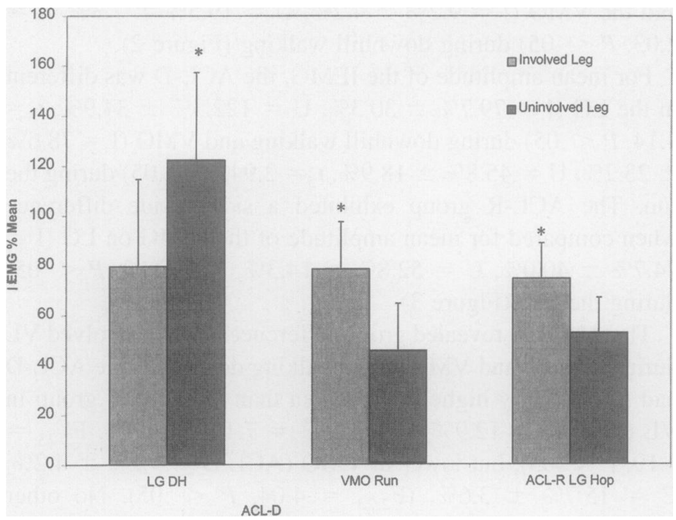

Figure 3. Significant side differences for mean IEMG of VMO and LG for ACL-D and ACL-R groups. Units are expressed as percentage of mean amplitude. DH, downhill walk; *, $P < .05$.

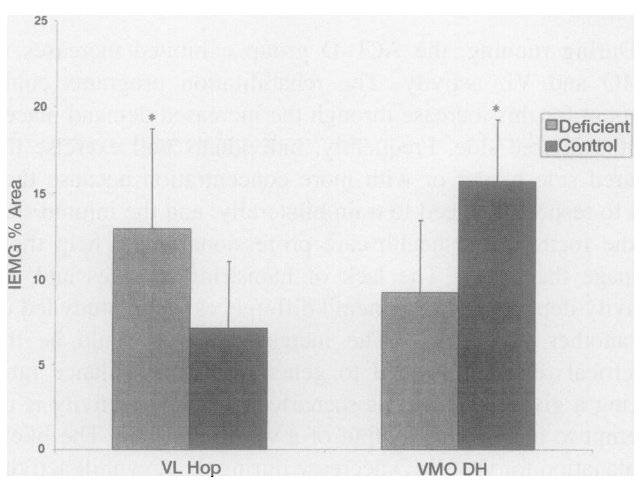

Figure 4. Significant group differences for IEMG area of vastus medialis and VL during hopping (Hop) and downhill walking (DH). Units are expressed as percentage of mean amplitude. *, $P < .05$.

limit the ATT force associated with this activity. This finding is consistent with those of Tibone and Antich[25] and McNair and Marshall.[26]

Contrasting results were found in the LG for landing (higher in area) and downhill walking (lower mean). These results could primarily be from foot position during the activity. In landing, since the activity involves slowing of the foot into dorsiflexion, there could be a higher level of activity because of increased tension. In contrast, downhill walking gait slows the foot into plantar flexion to avoid a drop-foot mechanism. This action increases demand on the tibialis anterior, resulting in a reciprocal inhibition to the posterior musculature and reducing EMG activity.

The LG differences were recorded during the various activities and therefore were not directly comparable, but they bring to light the issue of analysis technique. The mean amplitude is more robust to variance in the signal than the area and therefore less powerful to detect comparative differences. A third technique not used in this experiment is comparison of the peak signal, which marks the highest activity in the designated time period. Further research needs to be completed to determine whether the average activity, the total area of activity, or the maximum amount of activity is the best measurement technique for this type of comparison analysis.

Examining the results of this study revealed trends as to which muscles were consistently affected by this injury. The VMO showed differences bilaterally with the downhill walking and running activities. Group differences were also revealed. The VL also showed differences in running and landing and among groups. The LG revealed differences in downhill walking and landing. The point of repeating these results is to categorize them by muscle and group. All these bilateral differences are in the ACL-D group, while the ACL-R group revealed a difference only in the LG for the hop. Three points are important to this discussion. The first is the potential for different strategies within a muscle dependent on activity. Second, the improvements in proprioceptive ability may account for a return to bilateral normalcy. Third, our results could be due to divisions of muscles within units.

The movement strategy could change due to different activities.[16] This argument was mentioned regarding the differences between the medial gastrocnemius and LG and is supported by our results indicating LG differences depending on activity (land, downhill walk, and hop, which are not detected in the medial gastrocnemius). As movement patterns change, the forces on the muscles change. Because preactivity was examined in this study, the anticipation of the activity was likely responsible for the differences before footstrike. ATT forces seem to change with different activities.[9,10,11,27–31] This change in force, however, does not lead us to an expected finding. Typically, we would expect to see an increase in the hamstring activity in order to protect the joint, especially when the ACL is subject to additional stress or a position that stretches the remaining structures.[4,5,12,15,32,33] We did not find an increase in mean activity or area of the hamstrings. In examining the quadriceps, the expected change in force does appear to have an effect on preactivity level. For example, the VMO activity is lower on the involved side during the downhill walk. This strategy is thought to decrease ATT.[12,28] Although others[25,26] have shown a decrease in portions of the quadriceps muscle, Huston and Wojtys[4,5] suggest that the quadriceps are the dominating muscle in the athletic female based on reflex studies. Our results suggest less VMO activity during some movement patterns, indicating that, depending on the athlete's functional pattern, the quadriceps may not be the dominating factor. It is yet to be determined whether the decrease in preactivity affects the activity level in the postfootstrike period. Further study is required to support the claim of quadriceps domination in females.

Improvements in proprioceptive ability may provide an explanation for why bilateral differences were found in the ACL-D group but not in the ACL-R group, except for the LG during the hop. It has been stated that kinesthesia and position sense improve with surgical intervention,[20] but perhaps not to the level of the uninjured limb.[19] In our study, the ACL-R group differed only in one muscle for one activity. Because of the surgical reconstruction, the ACL-R group may have developed better position sense and kinesthesia and was therefore able to exhibit more (equal to uninvolved side) preparatory activity.

The third explanation for differences in the results within muscle groups is unit differentiation, where the different sections of a muscle are expected to act asynchronously. A natural expectation of the activity within a muscle for a given movement is that muscle sections such as the quadriceps (excluding the rectus femoris because of its 2-joint nature) would function in a similar style. That is, if the VMO had decreased in output going downhill in an attempt to reduce ATT, the VL would follow suit. In our experience, this did not occur. The explanation for this phenomenon is that muscle unit portions function differently depending on the movement pattern. In the quadriceps, the VMO and VL have been reported as responsive to medial and lateral knee stress, respectively.[34] It has been shown that, within muscle, there are different excitations dependent on activity.[35–37] These responses appear to apply to preparatory activity.

Further questions brought up by this study that require investigation are (1) whether EMG differences, and especially decreases, are the response of decreased muscle tone and (2) how EMG differences affect the muscle activity after foot contact. A correlation between preparatory and reactive muscle activity is warranted. Increased muscle activity before and after footstrike is important for stabilization. We speculate that the timing and order of contraction are also important and provide the basis for further investigation. An additional issue is whether these findings and associated explanations are true for males.

CONCLUSIONS

Side-to-side differences for the ACL-D and ACL-R groups and group differences between ACL-D and control suggest that, when performing different functional activities, ACL-D females use unique strategies involving the VMO, VL, and LG and that, therefore, these muscles require detailed examination. The quadriceps strategy may be explained by quadriceps (VMO) avoidance or VMO/VL ratio changes resulting from protective patterns or accommodation. Because a similar trend occurred with the gastrocnemius, muscle unit differentiation is the likely cause of our results. These changes appear to be reversed through surgery or the associated postoperative rehabilitation.

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