Females Recruit Quadriceps Faster Than Males at Multiple Knee Flexion Angles Following a Weight-Bearing Rotary Perturbation

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Objective: To compare the effect of knee angle on muscle response times and neuromuscular recruitment patterns between sexes following a perturbation in single leg stance at 10°, 20°, and 30°. We hypothesized that response times would be faster at lesser knee flexion angles and that females would recruit their quadriceps faster than males at all angles.

Design: A repeated-measures design.

Setting: Motion analysis laboratory.

Participants: Twenty (10 female; 10 male) healthy, recreationally active volunteers.

Interventions: A rotary perturbation in single leg stance.

Outcome Measurements: Response times of the medial and lateral quadriceps, hamstrings, and gastrocnemius.

Results: There was a trend toward faster response times for all muscles closer toward extension. A consistent neuromuscular recruitment pattern for both males and females was evident for each knee angle tested. Females, however, contracted their quadriceps faster than males at all knee flexion angles.

Conclusions: Small changes in knee angle near extension do not alter muscle response times and hence neuromuscular recruitment patterns in males and females. Regardless of knee flexion angle, following a perturbation in single leg stance, females contract their quadriceps faster than males.

Clinical Relevance: Earlier contraction of the quadriceps in females may increase anterior tibial translation and hence anterior cruciate ligament strain, thereby heightening injury risk.

Key Words: anterior cruciate ligament, knee angle, perturbation, reflex

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Functional knee joint stability results from a complex interaction among bony architecture, negative intra-articular pressure, compressive load, and active (neuromuscular) and passive (capsuloligamentous) restraints.[1,2] It has been suggested that the neuromuscular system has the primary responsibility of attenuating external moments and forces, thereby protecting the knee joint from injury.[1,3,4] The alarming rate of anterior cruciate ligament (ACL) injuries in the female athletic population implies inadequate contributions from the neuromuscular system.[5] Supporting this premise, females have been reported to have decreased quadriceps and hamstring strength,[6–8] decreased hamstring/quadriceps ratios,[9,10] increased time to generate peak hamstring torque,[6] decreased active hamstring stiffness,[11–13] decreased knee joint proprioception,[14] and undesirable neuromuscular response characteristics[6,15,16] compared with males.

Female neuromuscular response characteristics are frequently cited as an ACL injury risk factor.[17–19] Specifically, several investigators have identified that females rely on their quadriceps to a greater extent compared with males in response to a sudden joint loading.[6,10] As a quadriceps contraction near the end range of extension results in increased anterior tibial translation and strain upon the ACL, an earlier contraction of the quadriceps may increase injury risk, thereby jeopardizing joint stability.[20,21]

Sex differences in lower extremity neuromuscular characteristics, particularly muscle response times, however, have been inadequately investigated. In fact, only 2 studies have formally compared neuromuscular recruitment patterns and response times following a perturbation between sexes.[6,16] Utilizing a partial weight-bearing model, Huston and Wojtys[6] examined reflex latencies and neuromuscular recruitment patterns in male and female athletes and controls following a perturbation applied to the posterior aspect of the calf. The authors reported that female athletes tended to rely more heavily on their quadriceps and gastrocnemius musculature following the perturbation when compared with males. Using a full weight-bearing model in single leg stance, Shultz et al[16] measured the neuromuscular characteristics of male and female athletes following a sudden internal and external rotary perturbation. The investigators identified similar recruitment patterns (gastrocnemius [G], hamstring [H], quadriceps [Q]) between male and female athletes; however, females recruited their quadriceps approximately 10 ms faster than males.

Both of these reports, while insightful, examined the neuromuscular responses with the tibiofemoral joint in 30° of flexion. As ACL injury has been estimated to occur between 10 and 30°,[22,23] information related to neuromuscular characteristics within this range may assist with further elucidating the root of the gender disparity. Therefore, the purpose of our study was to compare male and female muscle response times at 10°, 20°, and 30° of knee flexion in single leg stance following either a sudden internal or external rotary perturbation of the femur on a fixed tibia. We hypothesized that females would recruit their quadriceps faster than males and that muscle response times would be fastest at 10°, followed by 20° and then 30° for all participants.

METHODS

Subjects

Ten male (height = 174.9 ± 6.4 cm; weight = 82.2 ± 14.3 kg; age = 30.6 ± 6.8 years) and 10 female (height = 163.0 ± 5.5 cm; weight = 64.0 ± 10.6 kg; age = 24.6 ± 4.3 years) recreationally active university students with no recent history of lower extremity pathology or conditions that would prevent pain-free participation volunteered for this study. Recreationally active was defined as participation in regular (2–4 times/wk) aerobic and/or anaerobic exercise. Before participating, all subjects read and signed an informed consent form approved by the Institutional Review Board, which had also approved the study.

Instrumentation

The instrumentation used in this study was identical to that of previous published work from our laboratory.[16,24] Specifically, we used an 8-channel Myosystem 2000 EMG (Noraxon; Scottsdale, AZ) to record the long latency response of the medial and lateral quadriceps, hamstrings, and gastrocnemius muscles. Unit specifications included an amplifier gain of 1 mV/V, a frequency bandwidth of 16 Hz to 500 Hz, CMRR 114 dB, input resistance from 20 MOhm to 1 GOhm, and a sampling rate of 1000 Hz. Bipolar Ag-AgCl surface electrodes (Medicotest; Olstykke, Denmark) measuring 10 mm in diameter with a center to center distance of 2.0 cm were used to detect the electromyographic (EMG) signal. We used Data Pac 2000 Version 2.32 Laboratory Applications System software (Run Technologies; Laguna Hills, CA) to acquire, store, and analyze the EMG data. A custom-built lower extremity perturbation device (LEPD; University of Virginia, Charlottesville, VA) was used to induce both the weight-bearing perturbations. A perturbation was defined as the rapid application of a force to challenge postural reaction. Lastly, we used a Chattecx balance device (Chattanooga Group Inc, Chattanooga, TN) and a Penny and Giles XM180 Electrogoniometer (Biometrics Ltd, Gwnet, UK) to standardize postural position and knee flexion angle before the perturbation.

Procedures

All subjects reported to the University's Sports Medicine/Athletic Training Research Laboratory for testing. As the rate of ACL injury is similar between dominant and nondominant lower extremities,[25] we counterbalanced dominant and nondominant lower extremities when testing. Leg dominance was defined as the leg the subject preferred to kick a ball with. Surface electrodes were placed halfway between the motor point and the distal tendon of the medial and lateral quadriceps and over the midbelly of the medial and lateral hamstring and gastrocnemius muscles after the skin was cleaned with isopropyl rubbing alcohol. To ensure proper electrode placement and the absence of crosstalk, muscle activity was observed on an oscilloscope during isolated manual muscle testing. Once the myoelectric signal was confirmed, an electrogoniometer was centered with double-sided adhesive tape over the lateral joint line with the proximal sensor aligned with the greater trochanter and the distal sensor with the lateral malleolus. All electrodes, their leads, and the electrogoniometer were secured circumferentially with an elastic wrap to minimize movement artifact. Careful attention was given to ensure all leads were of sufficient length to minimize undue tension at the lead-electrode and/or electrode-skin interface.

Next, a 3-in-wide nylon belt (Speed City Inc, Portland, Oregon) with 2 Kevlar cables was centered over the subject's anterior superior iliac spines and then fastened around their waist. The subject was then oriented to the Chattecx balance platform and LEPD. The LEPD was adjusted so that the cables, when attached to the release mechanisms of the device, were aligned in a horizontal manner and tensioned symmetrically. Subjects stood with their test leg on the foot plate of the Chattecx balance system, with their arms across their chest, trunk straight, leaning into the cables, with knee flexed to 10°, 20°, or 30° (Fig.1). The footplate of the Chattecx was sized so that approximately ½ in of clearance was present both in front of the toes and behind the heel. While in the test position, subjects were instructed to distribute their center of pressure equally between their toes and heel as best as they could. The display monitor on the Chattecx provided continuous visual feedback and the examiner gave verbal cues as necessary. Several practice trials of internal (IR) and external rotation (ER) perturbations were performed at each knee angle until the subject was comfortable with the procedure.

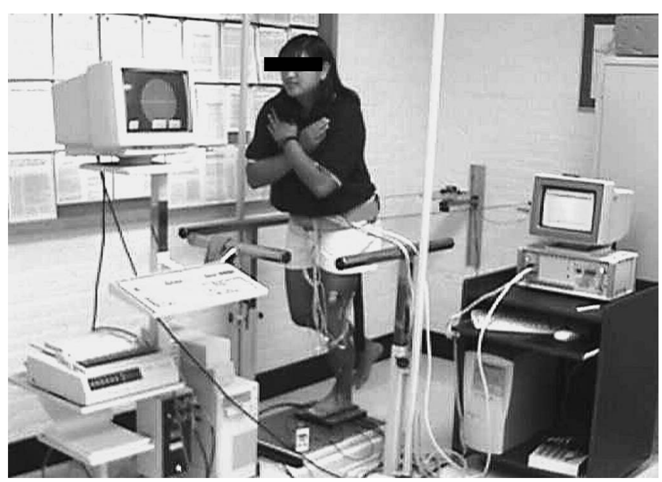

FIGURE 1. Subject positioning on lower extremity perturbation device.

The direction of the cable release (IR or ER) was defined in relation to the rotation of the trunk and femur following the perturbation. For example, a right cable release standing on the right foot was defined as an IR perturbation, whereas a left cable release standing on the right foot was defined as an ER perturbation. Immediately following the perturbation, subjects were encouraged to try to maintain their balance as best they could. The 30° knee angle was always tested first, while the 10° and 20° angles were counterbalanced. This delimitation was necessary as these data were part of a larger study. The perturbation direction was performed in a random fashion until 10 perturbations of each direction (IR and ER) were completed at each of the 3 knee angles.

Data Processing

All EMG signals were processed with the root mean square method with a 5-ms time constant. EMG activity was collected on a trigger sweep mode activated by release of the cable from the perturbation device. Initially, trials were separated into IR and ER perturbations. For each perturbation condition and knee angle, the first 5 trials that met the following criteria were signal averaged: 1) visible response from all muscles between 50 and 150 ms, and 2) acceptable signal to noise ratio (Fig. 2). To determine muscle response time, an event buffer for each muscle was established. An event was identified when the signal exceeded 2 SDs above a reference baseline (100 ms before cable release) for the medial and lateral hamstring and gastrocnemius muscles and 1 SD for the quadriceps. The time delay (milliseconds) from cable release to the event was defined as the muscle response time for the respective muscle. Selection of trials and determination of muscle response times was performed by the first author (C.R.C.). The reliability of these methods has been previously reported.[24]

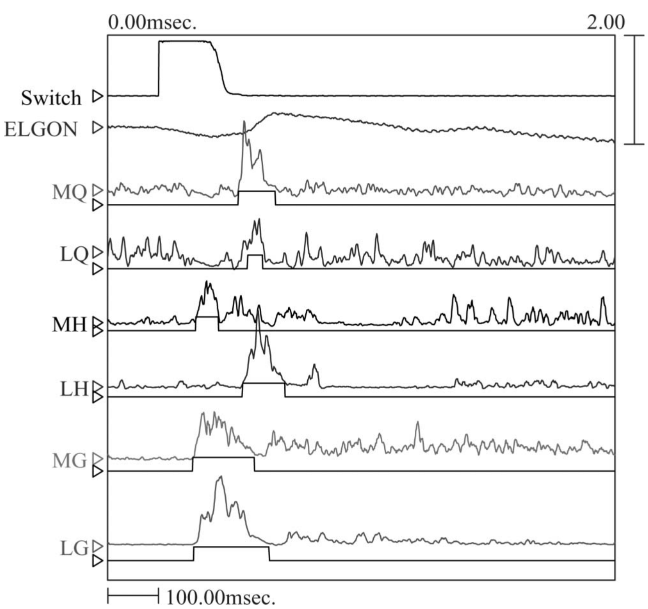

FIGURE 2. Signal averaged response for all muscles following a lower extremity perturbation. ELGON, Electrogoniometer.

Statistical Analyses

A repeated-measures analysis of variance with 3 within factors (perturbation type [internal, external], knee angle [10°, 20°, 30°], muscle [medial gastrocnemius, MG; lateral gastrocnemius, LG; medial hamstring, MH; lateral hamstring, LH; medial quadriceps, MQ; lateral quadriceps, LQ]) and 1 between factor (sex) evaluated the influence of knee flexion angle on muscle response times between sexes. α Levels were set a priori at $P < 0.05$. Post hoc analysis was performed with multiple comparisons and Bonferroni correction.

RESULTS

As response times for each muscle were not different between perturbation condition ($P = 0.66$) and interactions between perturbation condition and knee angle ($P = 0.14$), gender ($P = 0.90$), or muscle ($P = 0.29$) were not apparent, muscle response times from the internal and external rotary perturbations were grouped for all analyses. There was a trend toward faster muscle response times closer toward extension (10° = 81.8 ms; 20° = 84.7 ms; 30° = 85.7 ms); however, these differences were not significant ($P = 0.08$). Furthermore, knee angle did not influence muscle response times by sex ($P = 0.39$) or by muscle ($P = 0.81$). We did, however, observe a main effect for response times by muscle ($P < 0.001$; Fig. 3). Specifically, response times were first detected in the MG (62.0 ms), LG (65.1 ms), and MH (73.6 ms). Next, activation of the LH (90.0 ms) was noted, which, while not significantly different from MQ (105.2 ms), was faster than the LQ (108.3 ms). MQ and LQ activation were not different from each other. Though muscle group recruitment order was similar between sexes, there was a muscle by sex interaction ($P = 0.01$). Post hoc analysis identified that female participants recruited their quadriceps faster than males participants (Table 1).

DISCUSSION

Our primary finding identified a recruitment order of G-H-Q with faster quadriceps muscle response times in

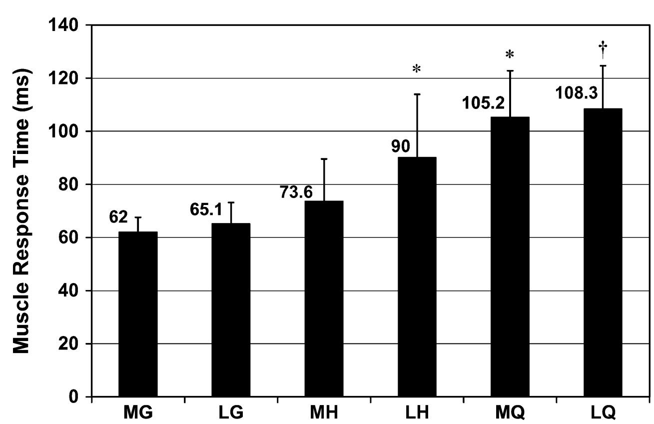

FIGURE 3. Overall average muscle response times following perturbation in single leg stance. *LH and MQ > MG, LG, and MH. †LQ > MG, LQ, MH, and LH but not MQ.

TABLE 1. Muscle Response Time by Sex

Muscle	Male	Female
MG	61.2 (6.7)	62.8 (8.4)
LG	63.9 (10.2)	66.3 (11.5)
MH	73.3 (21.1)	73.9 (17.3)
LH	86.9 (24.4)	93.1 (30.8)
MQ	112.1 (28.6)	98.2* (21.1)
LQ	118.0 (28.4)	98.6† (18.3)

Mean (SD) response times in milliseconds for all muscles delineated by sex following a rotary perturbation in single leg stance.
*Male and female MQ muscle response times significantly different.
†Male and female LQ muscle response times significantly different.

females. Our secondary findings were that muscle response times did not vary as a function of knee flexion angle in either males or females following a sudden perturbation in single leg stance.

Muscle Response Times and Recruitment Order

Muscle response times indicated a recruitment order of G-H-Q for all subjects. This recruitment order agrees with past work from our laboratory using the same model[16,24] and further demonstrates that neuromuscular recruitment order following a posterior to anterior rotary type of perturbation in the healthy weight-bearing knee is not only consistent but also independent of knee angle. The response times for all muscles in our sample, however, were slower on average for both male (11 ms) and female (13 ms) subjects when compared with those reported by Shultz et al.[16] This finding is likely explained by the activity level of the subjects. Shultz et al[16] examined response times from Division I collegiate athletes, while our sample consisted of general university subjects who were recreationally active. As athletes characteristically exhibit faster muscle response times compared with controls,[6] this finding was not a surprise.

Our findings are in contrast with those reported by Huston and Wojtys,[6] who did not identify differences in gastrocnemius and medial and lateral hamstring and quadriceps long latency response times between male and female athletes and controls following a perturbation applied to the posterior aspect of the calf. Methodological differences including weight-bearing status and type of perturbation may in part explain the contrasting findings. However, Huston and Wojtys[6] did report that female athletes tended to exhibit increased quadriceps activity and decreased hamstring activation during this intermediate, long latency phase. While our recruitment order was similar between sexes, females recruited their quadriceps faster across all knee flexion angles compared with males. Mean differences between sexes were 13.9 and 19.4 ms for the medial and lateral quadriceps, respectively. These mean sex differences were slightly greater than the 10-ms difference reported by Shultz et al.[16]

Why females tend to rely more heavily on their quadriceps remains unclear. Other biomechanical variables such as height and weight warrant exploration. As females on average weigh less than males, it is possible that mass and the moment of inertia account in part for this phenomenon. Interestingly, however, females demonstrated only faster response times in the quadriceps musculature, while the hamstring and gastrocnemius muscles were not significantly different from the male group. Clearly, further work is necessary to account for these findings.

Knee Angle

As the knee progresses closer to extension, ACL strain increases.[26] Modest (5–40 N) increases in ACL strain render muscle spindle afferents more sensitive to stretch via increased activity from the gamma motor system.[1] For this reason and based on the fact that a greater number of joint afferents discharge near end ranges of motion,[27] we hypothesized that muscle response times would be faster at lesser knee flexion angles. Though there was a trend toward faster response times closer to extension, these differences were not significant. This suggests that reflex velocity is not affected by small changes in joint angle near extension following a perturbation in a weight-bearing posture. While it may have been possible to achieve statistical significance by adding subjects, it was our opinion that there was little clinical significance of a 4-ms difference in response times.

Equally important, male and female subjects responded in a similar fashion as knee angle was varied. As noted, there was a trend for both groups to respond faster closer to full extension. This implies that while noncontact ACL injuries seem to be more prevalent near 20° of knee flexion[22,23] and in females, muscle response times do not appear to behave differently between sexes at 10°, 20°, or 30° following a perturbation in single leg stance.

Clinical Relevance

A laboratory model that simulates the mechanism of injury in a controlled yet functional manner is critical to gain a better understanding of what is occurring during activity. These data lend additional credence to the theory that females rely on their quadriceps to a greater extent compared with males. Furthermore, since response times for both sexes did not change by knee flexion angle, and quadriceps dominance in females was noted in both the previous (competitive)[16] and current (recreational) studies, it is likely that the findings by knee flexion angle for the competitive female would hold true. Earlier contraction of the quadriceps may place females at increased risk of ACL injury, particularly toward the end range of extension, where the hamstrings have a limited ability to restrain anterior tibial translation.[28] This recruitment characteristic may be particularly pertinent in the lesser trained, noncompetitive individual whose sport-specific movement patterns are less refined than those of the trained competitive athlete. However, while evidence is scarce, it does appear that neuromuscular response times are capable of being altered with training.[29,30] Future studies should determine the effectiveness of a training program on quadriceps latencies in females using the present as well as other models. To enhance knee joint stability, a program that results in faster hamstring and delayed quadriceps responses in females would seem to be desirable.

Study Limitations

To examine the influence of knee angle on muscle response times, we studied healthy recreationally active university students. As ACL injuries do occur in recreationally active females, this was a reasonable population to examine. The results, however, should be generalized only to this specific population. Also, we assumed that the stresses at the knee created by the perturbation were similar to those experienced during functional activities that stress the ACL.

CONCLUSION

Independent of knee angle, females elicit a quadriceps contraction faster than males following a sudden perturbation. Small changes in knee angle near terminal extension do not alter muscle response times and hence neuromuscular recruitment patterns following a weight-bearing rotary perturbation in single leg stance in the healthy knee.

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