Journal of Athletic Training 2008;43(2):133–143

www.nata.org/jat

Muscle Activation During Side-Step Cutting Maneuvers in Male and Female Soccer Athletes

Ashley M. Hanson, MA, ATC; Darin A. Padua, PhD, ATC; J. Troy Blackburn, PhD, ATC; William E. Prentice, PhD, PT, ATC; Christopher J. Hirth, PT, ATC

University of North Carolina, Chapel Hill, NC

Context: Female soccer athletes are at greater risk of anterior cruciate ligament (ACL) injury than males. Sex differences in muscle activation may contribute to the increased incidence of ACL injuries in female soccer athletes.

Objective: To examine sex differences in lower extremity muscle activation between male and female soccer athletes at the National Collegiate Athletic Association Division I level during 2 side-step cutting maneuvers.

Design: Cross-sectional with 1 between-subjects factor (sex) and 2 within-subjects factors (cutting task and phase of contact).

Setting: Sports medicine research laboratory.

Patients or Other Participants: Twenty males (age = 19.4 ± 1.4 years, height = 176.5 ± 5.5 cm, mass = 74.6 ± 6.0 kg) and 20 females (age = 19.8 ± 1.1 years, height = 165.7 ± 4.3 cm, mass = 62.2 ± 7.2 kg).

Intervention(s): In a single testing session, participants performed the running-approach side-step cut and the box-jump side-step cut tasks.

Main Outcome Measure(s): Surface electromyographic activity of the rectus femoris, vastus lateralis, medial hamstrings, lateral hamstrings, gluteus medius, and gluteus maximus was recorded for each subject. Separate mixed-model, repeated-measures analysis of variance tests were used to compare the dependent variables across sex during the preparatory and loading contact phases of each cutting task.

Results: Females displayed greater vastus lateralis activity and quadriceps to hamstrings coactivation ratios during the preparatory and loading phases, as well as greater gluteus medius activation during the preparatory phase only. No significant differences were noted between the sexes for muscle activation in the other muscles analyzed during each task.

Conclusions: The quadriceps-dominant muscle activation pattern observed in recreationally active females is also present in female soccer athletes at the Division I level when compared with similarly trained male soccer athletes. The relationship between increased quadriceps activation and greater incidence of noncontact ACL injury in female soccer athletes versus males requires further study.

Key Words: electromyography, anterior cruciate ligament, preparatory phase, loading phase, sex differences

Key Points

- During a side-step cutting maneuver, female collegiate soccer athletes demonstrated more vastus lateralis activation than male collegiate soccer athletes did.
- Female collegiate soccer athletes demonstrated larger quadriceps-to-hamstrings coactivation ratios than male collegiate soccer athletes, indicating that the females did not increase their hamstrings activation to compensate for increased quadriceps activation.
- The sex differences in quadriceps activation and quadriceps-to-hamstrings coactivation ratios observed in recreational athletes were also present in highly trained and skilled collegiate soccer athletes.

Understanding anterior cruciate ligament (ACL) injury risk factors is an area of great interest due to the increased risk of ACL injury in females compared with males.[1–8] In addition to sex, the risk of ACL injury is also influenced by the sport in which an individual participates. Females participating in basketball and soccer at the National Collegiate Athletic Association (NCAA) level have been shown to be at greater risk for ACL injury than their male counterparts.[1,2] More recent research shows that the rate of ACL injury is still higher in female soccer and basketball athletes than in male soccer and basketball athletes; however, the rate of ACL injury (number of ACL injuries per 1000 athlete-exposures) is significantly greater in female soccer athletes (ACL injury rate = 0.33 per 1000 athlete-exposures) compared with female basketball athletes (0.27 per 1000 athlete-exposures).[9] Based on these findings, female soccer athletes appear to be at greatest risk for sustaining an ACL injury. To better understand potential risk factors for ACL injury, it is important to focus research on those individuals who are at the highest risk, such as female soccer athletes.

Neuromuscular properties that influence the magnitude of ACL loading are considered possible risk factors for ACL injury. Loading of the ACL may occur in multiple planes, as anterior tibial translation,[10–16] knee valgus,[17] and lower extremity rotational[18–20] motions all increase the amount of load on the ACL. Contraction of the quadriceps[10–16] and hamstrings[14,16,21–23] muscles greatly influences the development of anterior tibial shear force and the resulting anterior tibial translation that strains the ACL. Knee valgus motion is thought to be influenced by hip mechanics during weight-bearing tasks. Specifically, the closed kinetic chain theory suggests that excessive hip adduction and rotation may facilitate increased knee valgus motion. However, the relationship between knee valgus with hip adduction and rotation is based on anecdotal evidence. According to this theory, the magnitude of ACL loading due to knee valgus and rotational motions may be influenced by contraction of the gluteus medius and gluteus maximus, as these muscles have been shown to control hip adduction and internal rotation during weight-bearing tasks.[24–26] Thus, activation of the quadriceps, hamstrings, gluteus medius, and gluteus maximus muscles plays a role in ACL loading by influencing anterior tibial translation, knee valgus, and lower extremity rotational motions.

Most research comparing muscle activation amplitude between males and females has focused on recreationally active individuals,[27–29] with limited attention focused on those who are at greatest risk for ACL injury, such as female soccer athletes.[30] Investigators of recreationally active individuals have shown that females demonstrated greater quadriceps activation compared with males during hopping,[29] cutting,[27] and lunging[28] maneuvers. Recreationally active females also exhibited decreased hamstrings activation[27] and altered coactivation ratios of the quadriceps and hamstrings.[29] Very few authors have compared gluteal muscle activation between the sexes. In a study of track and soccer athletes,[31] females displayed lower gluteus maximus activation during a single-leg landing than males; however, no difference was seen in gluteus medius activation. Other authors[32] revealed no sex differences in gluteus maximus and gluteus medius activation during a single-leg squat task. Gluteal muscle activation during a task that is commonly associated with noncontact ACL injury, such as side-step cutting, has not been investigated. Although these studies have provided important information about sex differences in muscle activation, a comprehensive evaluation of muscle activation patterns in a group of individuals at great risk while performing a task commonly associated with ACL injury has not been performed. Given that activation of those muscles associated with ACL loading (quadriceps, hamstrings, gluteus medius, and gluteus maximus) is a possibly important factor for ACL injury, research is needed to better understand the potential muscle activation patterns that may put female athletes at greater risk for ACL injury.

Our purpose was to compare the activation amplitude of the quadriceps, hamstrings, gluteus medius, and gluteus maximus muscles and the coactivation ratio of the quadriceps and hamstrings during side-step cutting between male and female Division I soccer athletes. Two different side-step cutting maneuvers were performed (running and box jump) to determine if muscle activation of males and females was influenced by the type of side-step cutting task performed. Also, muscle activation was assessed during the preparatory and loading phases of the side-step cutting tasks to determine if the phase of contact influenced the muscle activation of males and females.

We hypothesized that in comparison with male soccer athletes, female soccer athletes would demonstrate (1) greater quadriceps activation, (2) less hamstrings, gluteus medius, and gluteus maximus activation, and (3) increased quadriceps to hamstrings coactivation ratios. Understanding if sex differences in muscle activation exist among highly skilled athletes who are at high risk for ACL injury and who demonstrate the greatest disparity in ACL injury rates may lend additional insight into potential factors influencing the sex bias in ACL injury.

METHODS

Participants

We recruited 20 males (age = 19.4 ± 1.4 years, height = 176.5 ± 5.5 cm, mass = 74.6 ± 6.0 kg) and 20 females (age = 19.8 ± 1.1 years, height = 165.7 ± 4.3 cm, mass = 62.2 ± 7.2 kg) who were NCAA Division I varsity soccer players. To be eligible for participation, all participants had to meet the following criteria: (1) between 18 and 25 years of age, (2) member of the men's or women's varsity soccer team, (3) no previous history of ACL injury, and (4) no serious lower extremity injury in the past month that required missing practice for more than 3 consecutive days. Before the study, all participants read and signed an informed consent form approved by the Biomedical Institutional Review Board at the University of North Carolina, Chapel Hill, which also approved the study. All testing was performed during the soccer athlete's off-season (approximately 6 weeks after the last formal game or practice) and at least 24 hours after any physical training to minimize the possibility of fatigue and lingering muscle dysfunction associated with previous injury.

Instrumentation

We used an 8-channel Konigsberg surface electromyography (EMG) system (Konigsberg Instruments, Inc, Pasadena, CA) (input impedance = 200 kΩ, common mode rejection ratio >70 dB, signal-to-noise ratio >40 dB) and bipolar Ag-AgCl surface electrodes (Medicotest, Rolling Meadows, IL) measuring 10 mm in diameter with a center-to-center distance of 20 mm to record muscle activity. The EMG signal was amplified by a factor of 5000 over a bandwidth of 0.01 to 500 Hz and passed via an A/D converter (Measurement Computing Corp, Norton, MA) sampling at 1000 Hz to the storage computer. A nonconductive force plate (model 4060-NC; Bertec Corp, Columbus, OH) sampled at 1000 Hz was used to identify ground contact and the stance phase during the side-step cutting tasks. A Flock of Birds electromagnetic motion analysis system (Ascension Technologies, Inc, Burlington, VT) controlled by Motion Monitor data acquisition computer software (version 7.0; Innovative Sports Training, Inc, Chicago, IL) was used to measure horizontal movement velocity during the cutting tasks.

Testing Procedures

All testing was performed in a single testing session that lasted approximately 60 minutes. Participants were required to wear running shoes, athletic shorts, and a T-shirt during testing. The dominant leg of each participant, defined as the leg used to kick a ball for maximal distance, was the test limb. Participants rode a stationary bicycle for 5 minutes and then stretched their quadriceps, hamstrings, and gluteal muscles to warm up before testing commenced.

Participants were prepared for EMG electrode placement. The skin was shaved, abraded, and cleaned with isopropyl alcohol to reduce impedance. Surface electrodes were secured using prewrap to prevent movement artifact and tension on the cables during the side-step cutting maneuver. Surface electrodes were placed in a parallel arrangement over the muscle bellies of the rectus femoris (RF), vastus lateralis (VL), medial hamstrings (semitendinosus and semimembranosus) (MH), lateral hamstrings (long head of biceps femoris) (LH), gluteus medius (GMED), and gluteus maximus (GMAX). Electrode placement for the gluteus medius was halfway between the iliac crest and the greater trochanter of the femur.[33] The electrodes for the gluteus maximus were placed 20% of the distance between the spinous process of the second sacral vertebrae and a point 10 cm distal to the greater trochanter.[34] Electrode placement for the quadriceps and hamstrings was determined by palpating the length of the muscle belly and identifying the midsection. A reference electrode was placed on the tibial tuberosity. Proper electrode placement was verified by performing manual muscle tests and viewing the output on an oscilloscope (Tektronix, Inc, Beaverton, OR).

The participant was then placed in a seated position on an isokinetic dynamometer (Biodex Medical Systems, Inc, Shirley, NY) to perform maximal voluntary isometric contractions (MVICs) for each of the muscles being tested. To obtain MVIC for the quadriceps and hamstrings, the participant flexed the knee of the test limb to 45° while performing an isometric contraction against the lever arm of the dynamometer into extension for the quadriceps and into flexion for the hamstrings.[34] The MVIC testing for the gluteus medius was performed with the participant in a side-lying position on the nondominant limb with a hook-and-loop strap over the iliac crest to provide stability. The hip of the participant's test limb was held in 10° of extension and the knee in full extension. While in this position, the participant pushed against the stationary lever arm of the dynamometer with maximal effort. Gluteus maximus MVIC was determined by having the volunteer in a prone position with a hook-and-loop strap placed over the hips to provide stability. With the knee fully extended, the participant was asked to extend the leg into the air against the manual resistance of the tester. This position was chosen in order for the tester to be able to maintain good leverage over the athlete during the MVIC. The knee was held fully extended to prevent the tester's hand from coming in contact with the surface electrodes on the participant's hamstrings.

The MVIC values for each muscle were obtained by collecting 1 maximal 5-second trial[35,36] after a series of 3 warm-up trials performed at 50%, 75%, and 100% of maximal effort. The first and last seconds of the MVIC trial were removed from the data to ensure only steady-state results during the test. The average activity during the middle 3 seconds of the MVIC trial was determined for each muscle. The average muscle activation amplitude over this time period was then used to normalize the EMG data collected during the side-step cutting task for each muscle tested. Thus, EMG data were expressed as a percentage of MVIC (%MVIC). The order of muscle testing during MVIC assessment was randomized.

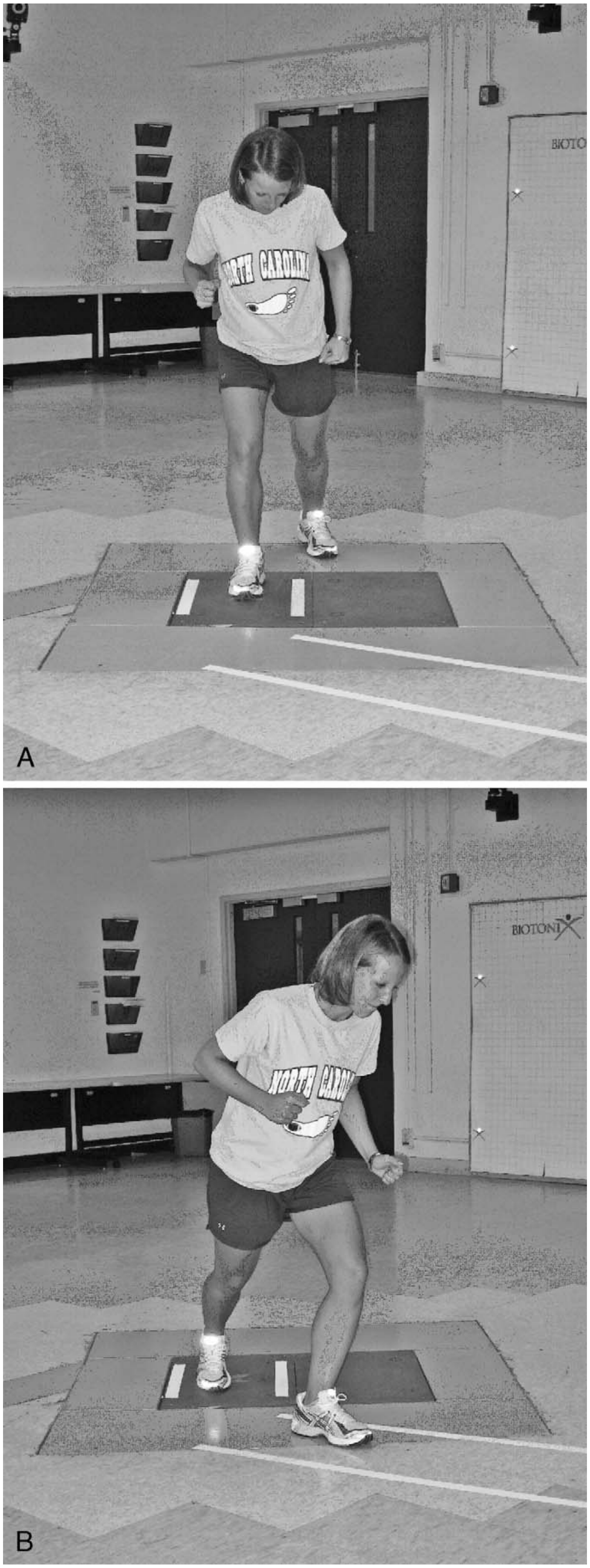
After completion of equipment and participant set-up, a demonstration of both side-step cutting maneuvers (running side-step cut and box-jump side-step cut) was provided for the volunteer. During the running side-step cut, the participant had 3.04 m to accelerate before performing the cutting task (Figure 1). The participant performed the side-step cutting task at an approach speed of 3.04 m/s. A digital metronome (Sabine, Inc, Alachua, FL) was used to provide an auditory cue for the participant to maintain the desired approach speed. The metronome was set at 60 beats/min, and the participant was instructed to begin running on the first beep and contact the force plate on or before the second beep. The instantaneous horizontal velocity of the electromagnetic sensor placed over the sacrum relative to the world was checked to ensure that the participant's approach speed was within ±5% of the desired approach speed. We only analyzed trials in which the instantaneous horizontal velocity of the sacral sensor was between 2.88 and 3.19 m/s. Upon reaching the force plate, the participant performed the side-step cut by placing the foot of the dominant leg in direct contact with the force plate, making sure the foot was facing straight ahead, and then cutting 60° in the direction opposite the planted leg. For example, a right-leg–dominant participant would plant and pivot to the left at 60°. To standardize the cutting angle, a 1-ft (0.3-m)–wide alleyway was marked on the ground extending from the force plate. The alleyway was placed at 60° relative to the participant's forward path of motion before contacting the force plate. While performing the side-step cutting motion, the participant was instructed to place the trail foot (nondominant leg) in the alleyway, so that the foot contacted the ground pointing in the direction of the alleyway. Only trials in which the participant's feet met these criteria were analyzed. Trials that did not meet the horizontal velocity and foot positioning criteria were discarded and repeated. After completing the side-step cut, the participants had 8 ft (2.4 m) of available space to decelerate before running out of laboratory space. This allowed for approximately 3 deceleration steps to be taken following the cutting motion. The participant performed 5 trials and was allowed a 30-second rest period between trials.

Athletes often change direction of motion after landing from a jump. In order to simulate this task, participants performed a side-step cut after jumping off a 30-cm-high box (box-jump side-step cutting task). The distance between the center of the force plate and the front of the box was 2/3 of the participant's body height (Figure 2). Each volunteer performed this box-jump side-step cutting maneuver by pushing off the box with the foot of the nondominant leg and lunging forward onto the force plate with the foot of the dominant leg. Immediately upon contacting the ground, the participant cut 60° in the opposite direction of the dominant leg, similar to the running side-step cutting maneuver. The participant performed 5 trials and was allowed a 30-second rest period between trials. The order of the box-jump and running side-step cutting maneuvers was randomized. Before data collection, the participant performed 3 practice trials to accommodate to the cutting maneuvers.

Data Processing and Reduction

After acquisition, all EMG data (cutting tasks and MVIC trials) were band-pass filtered (10 to 350 Hz) and notch filtered (60 Hz at 1-Hz width) using a Butterworth filter (4th order, zero-phase lag). The data were rectified and smoothed by taking the root mean square average of the EMG signal using a 20-millisecond sliding window function.

Mean EMG amplitudes were quantified to assess muscle activity for each muscle during the preparatory and loading phases of the side-step cutting maneuvers (running and box jump; Figure 3). The preparatory phase (PR) was defined as the 50-millisecond time period before ground contact. Initial ground contact was defined as the time when vertical ground



reaction force exceeded 5 N. The loading phase (LO) was defined as the initial 50% of the stance phase during the side-step cutting maneuver. The stance phase was defined as the time period between initial ground contact with the force plate until toe-off during the side-step cutting maneuvers. Toe-off was identified as the time when vertical ground reaction force dropped below 5 N. This LO was selected to assess the muscle activation immediately after ground contact, as this time period of deceleration has often been associated with noncontact ACL injuries.[1,2,37] Coactivation ratios for the quadriceps and hamstrings (Q:H) were also assessed during the PR and LO phases of both side-step cutting tasks. The Q:H coactivation ratio was computed as the sum of the average EMG amplitude of the quadriceps (RF and VL) divided by the sum of the average EMG amplitude of the hamstrings (MH and LH) for each trial.[29,38] The Q:H coactivation ratio was computed separately for each of the 5 trials, and then the average was taken for Q:H coactivation ratios. Coactivation ratios of 1.0 indicated equal average activation of the Q and H muscles. Coactivation ratios greater than 1.0 indicated increased Q average activation in comparison with H. Coactivation ratios less than 1.0 indicated greater H average activity compared with Q. All EMG data were collected over a 5-second time period centered on initial ground contact during the cutting tasks (2 seconds before and 3 seconds after initial ground contact).

Statistical Analyses

We performed separate, mixed-model, repeated-measures analyses of variance with 1 between-subjects and 2 within-subjects factors for each dependent variable (average EMG amplitudes and Q:H coactivation ratios). For all analyses, the between-subjects factor was sex (2 levels: male and female) and the within-subjects factors were cutting task (2 levels: running and box jump) and phase of contact (2 levels: PR and LO). Tukey post hoc analyses were performed to examine significant interactions. Statistical significance was set a priori at $\alpha \leq .05$. All data were analyzed using SPSS (version 14.0; SPSS Inc, Chicago, IL).

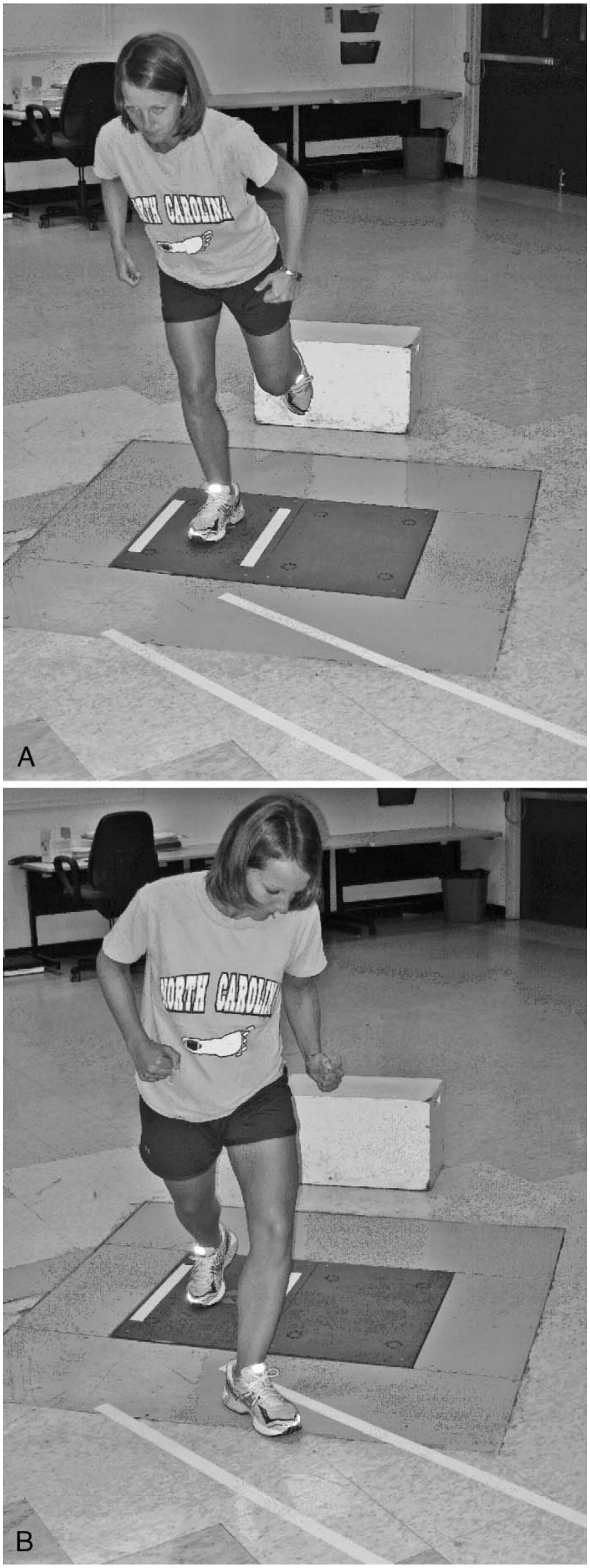
RESULTS

Means and SDs for average EMG amplitudes and Q:H coactivation ratios during the PR and LO phases of the running and box-jump side-step cutting maneuvers are listed in the Table.

Significant sex-by-phase interactions were noted for VL ($F_{1,38} = 11.87$, $P = .001$) and GMED ($F_{1,38} = 6.78$, $P = .013$) muscle activation amplitudes. Post hoc analyses of VL activation revealed that females demonstrated significantly greater VL activation than males during both the PR and LO phases and that VL activation significantly increased from the PR to the LO phase for both males and females (Figure 4). Post hoc analyses of GMED activation revealed no difference

←

Figure 1. Running-approach side-step cutting task. A, During the running side-step cutting task, the individual plants the foot of the dominant leg with the toes pointed forward along the path of motion and then, B, cuts 60° in the opposite direction of the planted foot. Foot positioning and cutting angle are controlled by having the subject place the foot in the alleyway marked on the floor.



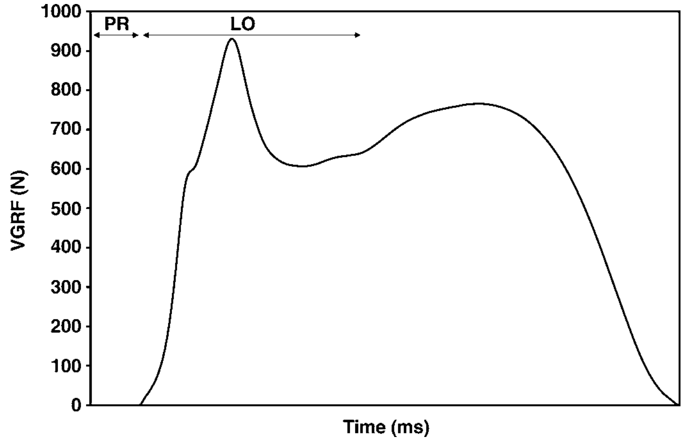


Figure 3. Preparatory phase (PR) was defined as the 50-ms time period before vertical ground reaction force rises above 5 N. The loading phase (LO) was defined as the first 50% of the stance phase during the side-step cutting tasks.

between the sexes during the PR phase; however, females showed GMED activation during the LO phase compared with males (Figure 5). Both males and females increased GMED activation from the PR to the LO phase. A sex main effect was seen for Q:H coactivation ($F_{1,38}$ = 7.423, P = .01), as females displayed a greater Q:H coactivation ratio than their male counterparts (Figure 6). No main effects or interactions involving sex (statistical findings for sex main effects are reported) were noted for activation amplitudes of the RF ($F_{1,38}$ = 1.834, P = .18, η_p^2 = .046, 1 − β = .262), MH ($F_{1,38}$ = 0.048, P = .82, η_p^2 = .001, 1 − β = .055), LH ($F_{1,38}$ = 0.035, P = .85, η_p^2 = .035, 1 − β = .054), or GMAX ($F_{1,38}$ = 0.197, P = .65, η_p^2 = .005, 1 − β = .07) muscles. Thus, males and females displayed similar muscle activation amplitudes during the PR and LO phases of both side-step cutting tasks for these muscles.

Main effects were identified for cutting task and phase of contact for the average amplitude of each muscle tested (Figures 7 and 8) and Q:H coactivation ratios. The main effects for cutting task revealed that activation during the running side-step cut was significantly greater than during the box-jump side-step cut for the VL ($F_{1,38}$ = 64.77, P < .001), RF ($F_{1,38}$ = 62.38, P < .001), MH ($F_{1,38}$ = 50.31, P < .001), LH ($F_{1,38}$ = 82.27, P < .001), GMED ($F_{1,38}$ = 64.81, P < .001), and GMAX ($F_{1,38}$ = 35.83, P < .001), as well as the Q:H coactivation ratio ($F_{1,38}$ = 8.807, P = .005) (running side-step cut = 1.14 ± 0.57, box-jump side-step cut = 1.00 ± 0.58). Phase of contact main effects demonstrated increases from the PR to the LO phase for the VL ($F_{1,38}$ = 125.29, P < .001), RF ($F_{1,38}$ = 94.35, P < .001), MH ($F_{1,38}$ = 57.33, P < .001), LH ($F_{1,38}$ = 4.42, P = .04), GMED ($F_{1,38}$ = 152.82, P < .001), and Q:H coactivation ($F_{1,38}$ = 64.05, P < .001) (PR = 0.84 ± 0.50, LO = 1.31 ± 0.55). However, GMAX ($F_{1,38}$ = 4.94, P = .03) activation displayed the opposite finding, with a decrease from the PR to the LR phase.

←

Figure 2. Box-jump side-step cutting task. A, During the box-jump side-step cutting task, the individual lunges forward off a 30-cm high box with the dominant leg. B, The foot of the dominant leg lands within the alleyway marked on the force plate, and the subject cuts 60° in the opposite direction of the planted foot.

Table. Muscle Activation Amplitude (% Maximal Voluntary Isometric Contraction) and Quadriceps:Hamstrings Coactivation Ratios for Male and Female Soccer Athletes During the Preparatory and Loading Phases of the Cutting Tasks (Mean ± SD)

		Running Side-Step Cut		Box-Jump Side-Step Cut	
Muscle Group	Sex	Preparatory Phase	Loading Phase	Preparatory Phase	Loading Phase
Maximal voluntary isometric contraction (%)					
Vastus lateralis	Males	129.36 ± 63.30	188.85 ± 61.60	51.57 ± 22.53	151.94 ± 50.47
	Females	186.14 ± 102.75	320.86 ± 164.65	77.15 ± 51.97	244.45 ± 128.24
Rectus femoris	Males	80.19 ± 47.84	136.73 ± 63.46	33.04 ± 19.53	107.17 ± 58.06
	Females	80.25 ± 38.46	173.32 ± 81.08	40.20 ± 26.41	140.55 ± 75.15
Medial hamstrings	Males	77.46 ± 57.63	128.02 ± 48.60	32.16 ± 24.80	106.64 ± 50.05
	Females	72.19 ± 34.75	130.22 ± 92.68	34.82 ± 20.57	119.37 ± 75.45
Lateral hamstrings	Males	194.92 ± 113.68	194.18 ± 143.23	137.35 ± 75.56	154.75 ± 133.71
	Females	172.29 ± 64.43	210.57 ± 85.13	122.53 ± 61.71	154.86 ± 69.38
Gluteus medius	Males	84.93 ± 48.53	138.42 ± 39.78	44.98 ± 34.08	123.58 ± 38.11
	Females	78.53 ± 45.42	173.30 ± 80.62	43.00 ± 29.03	150.82 ± 60.49
Gluteus maximus	Males	301.35 ± 264.17	186.08 ± 110.41	194.22 ± 159.23	172.22 ± 97.08
	Females	256.08 ± 175.68	194.73 ± 110.52	163.24 ± 131.60	167.93 ± 79.23
Quadriceps:hamstrings coactivation	Males	0.81 ± 0.26	1.08 ± 0.30	0.59 ± 0.29	1.12 ± 0.47
	Females	1.16 ± 0.74	1.55 ± 0.63	0.82 ± 0.45	1.51 ± 0.64

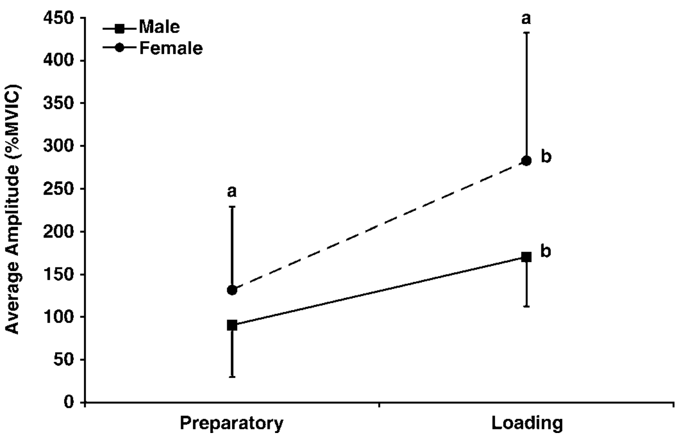


Figure 4. Influence of sex and phase of contact on vastus lateral activation. [a] Indicates a significant difference between male and female soccer athletes (P = .001). [b] Indicates a significant difference between the preparatory and loading phases of contact. MVIC indicates maximal voluntary isometric contraction.

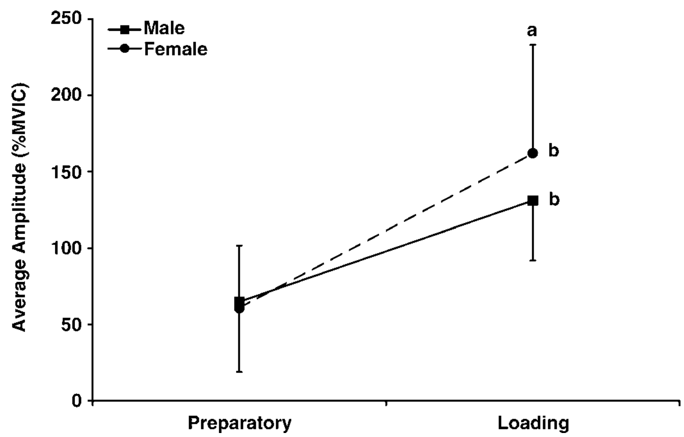


Figure 5. Influence of sex and phase of contact on gluteus medius activation. [a] Indicates a significant difference between male and female soccer athletes (P = .013). [b] Indicates a significant difference between the preparatory and loading phases of contact. MVIC indicates maximal voluntary isometric contraction.

DISCUSSION

Our first purpose was to compare Q, H, GMED, and GMAX activation amplitudes and Q:H coactivation ratios between male and female soccer athletes at the NCAA Division I level. A secondary purpose was to determine if the activation amplitudes and coactivation ratios of males and females were influenced by the type of cutting task performed and the phase of contact. The primary findings were that female soccer athletes exhibited greater VL activation amplitude and Q:H coactivation ratio than their male counterparts. Sex differences in VL activation and Q:H coactivation ratio were observed during both the PR and LO phases of side-step cutting. Also, sex differences were evident in GMED activation, as females demonstrated greater activation than males during the LO phase of side-step cutting but not during the PR phase. No sex differences were noted in muscle activation amplitude for the other muscles tested. We believe these findings indicate that female soccer athletes use a Q-dominant muscle activation pattern when performing tasks associated with noncontact ACL injury. We theorize that the Q-dominant muscle activation strategy used by female soccer athletes may place them at greater risk for noncontact ACL injury.

It is important to note that males and females performed the side-step cutting tasks under identical conditions (eg, controlled approach speed and cut angle); thus, the sex differences in VL activity are not attributable to performance differences. During the PR phase, the females scaled their VL activity to a larger extent than the men did (31% more than males). Greater reliance on VL activity by women was further demonstrated during the LO phase, as the differences between the sexes were even larger (40% more than males). These findings supported our original research hypotheses. Our results are also in agreement with the findings of other investigators reporting greater Q activation in females than males.[27–32,38,39] Malinzak et al[27] were the first to reveal greater Q activation in females than in males during a side-step cutting task. Our results extend this research, because we tested a population of Division I soccer athletes, whereas Malinzak et al tested recreational athletes, defined as persons who played basketball, volleyball, or soccer at least 3 times per week and did not

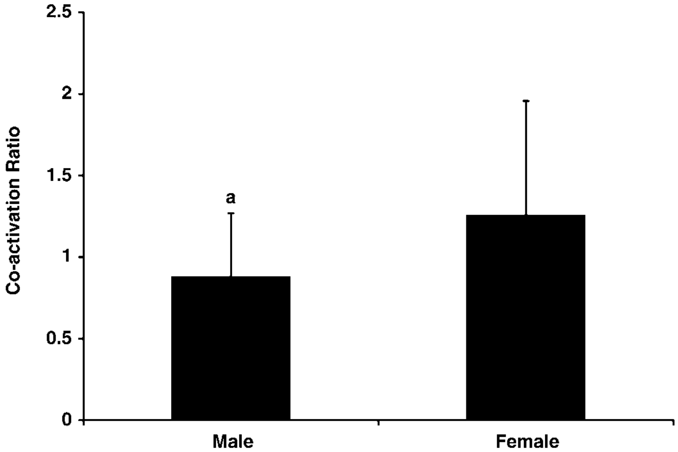


Figure 6. Influence of sex on quadriceps:hamstrings coactivation ratios (*P* = .01). [a] Indicates a significant difference between male and female soccer athletes.

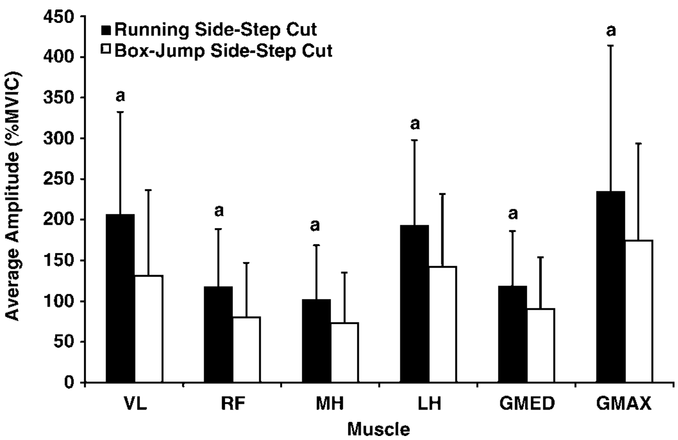


Figure 7. Influence of type of cutting task on average muscle activation amplitude. [a] Indicates a significant difference between the running and box-jump approach side-step cutting tasks (all *P* < .001). MVIC indicates maximal voluntary isometric contraction.

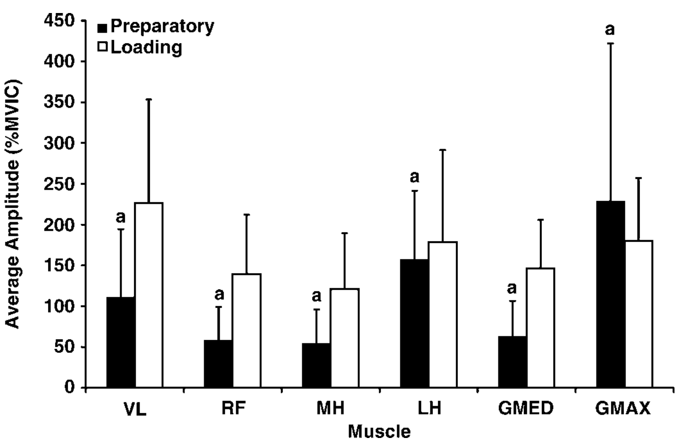


Figure 8. Influence of phase of contact on average muscle activation amplitude. [a] Indicates a significant difference between the preparatory and loading phases of the side-step cutting task (*P* < .05). Vastus lateralis, *P* < .001; rectus femoris, *P* < .001; medial hamstrings, *P* < .001; lateral hamstrings, *P* = .04; gluteus medius, *P* < .001; gluteus maximus, *P* = .03. MVIC indicates maximal voluntary isometric contraction.

follow a professionally designed training program. Based on our findings and those of previous researchers, increased Q activation in females compared with males is present in both the highly skilled and trained collegiate soccer athlete and in recreational athlete populations.

Because the magnitude of the sex discrepancy in ACL injury rate is not consistent across sports,[1,2,40] it is essential to study specific groups of athletes. For example, the sex bias in ACL injury rates does not appear to be present in sports such as volleyball and lacrosse[1,40] and is greater in soccer athletes than in basketball athletes.[1,2] Agel et al[9] reported that in comparison with basketball athletes, female soccer athletes were at the highest risk for ACL injury. Investigating female soccer athletes, who are at greatest risk for ACL injury, may further improve our understanding of potential ACL injury risk factors in females in general. Researchers have more recently shown that female collegiate athletes (soccer, basketball, and track) also displayed greater Q activity than male collegiate athletes.[30–32] However, only we and Sigward and Powers[30] have focused solely on female collegiate soccer athletes. Sigward and Powers[30] investigated NCAA Division I and II soccer athletes, whereas we specifically investigated NCAA Division I soccer athletes. In studying male and female soccer athletes at the NCAA Division I level from the same institution, a certain amount of consistency may be assumed in terms of the type of training and conditioning that each athlete has undergone, particularly because measures were taken during the same time of season for both sexes. Additionally, athletes at the NCAA Division I level have generally been involved in their particular sport from a very young age, regardless of sex. We feel that our findings extend previous research, as we focused on groups of males and females who participated in the same sport (soccer), were of similar skill level (NCAA Division I student-athletes), underwent similar strength and conditioning programs (verified by the team's certified athletic trainer and strength and conditioning coach), and had similar experience with performing side-step cutting tasks. Thus, sex differences in Q activation did not appear to be influenced by these factors.

Quadriceps contraction has been shown to increase ACL loading and increase the risk of ACL injury unless H muscle contraction is sufficient to counteract Q muscle contraction.[11,14,41] Our findings revealed no difference in activation of the medial and lateral H between males and females. Thus, even though female soccer athletes recruited more Q activation, they did not scale their H activation to similar levels. Our results agree with those of most previous researchers, indicating that H activation is similar between males and females.[29,30,32,38,39] Malinzak et al[27] were the only investigators to report decreased H activation in recreationally active females compared with males. As previously indicated, however, Malinzak et al[27] tested a recreational athlete population and did not indicate if the groups had similar experience and training levels, participated in the same sports, or had similar backgrounds in performing cutting maneuvers. Differences in these factors may influence H activation and the study's results, thereby limiting the ability to directly compare their study's findings with ours.

Perhaps the most intriguing finding of our study was that while H muscle activation was similar, sex differences were apparent in the Q:H coactivation ratio. Male soccer athletes displayed a Q:H coactivation ratio of 0.88 during the side-step cutting tasks, whereas the ratio for female soccer athletes was

1.26. Thus, female soccer athletes used a Q-dominant activation pattern, and male soccer athletes demonstrated a more balanced or H-dominant muscle activation pattern during the cutting tasks. Altered Q:H coactivation ratios between males and females have been reported by other investigators.[29,38,39] Previous researchers comparing Q:H coactivation ratios between the sexes have focused on hopping[29,38] and jump-landing tasks.[39] Our results agree with these previous studies and extend their findings by demonstrating greater Q relative to H activation in female NCAA Division I soccer athletes during 2 side-step cutting tasks.

De Luca and Mambrito[42] proposed the concept of a ''common drive'' existing between the Q and H. The authors suggested that simultaneous increases in activation between agonist and antagonist muscles are controlled by a central coactivation mechanism. When an agonist-antagonist pair of muscles is participating in a specific task, the common drive controls the motor units of each muscle, treating both muscles as a single entity.[42] The concept of a common drive that appropriately scales Q and H activation would be an effective mechanism to minimize anterior tibial shear forces at the knee joint. Based on our findings and those of others,[29,38,39] the common drive that facilitates Q and H coactivation appears to differ between the sexes, as female soccer athletes exhibited greater Q activation that was not associated with increased H activation. The observed differences in Q:H coactivation ratios between the sexes may have clinical relevance because ACL loading is influenced by Q[10–16,43] and H[14,16,21–23] activation; thus, an increased Q:H coactivation ratio may be a potential risk factor for ACL injury. Although the derivation of the sex difference in VL activity in our investigation cannot be readily discerned, it is important to note that this difference persisted in both the PR and LO phases. Greater VL activity during the LO phase could be related, at least partially, to sex differences in landing kinematics,[27,30,44–47] which impose a greater internal moment requirement on the Q. However, the fact that this difference was also present during the PR phase suggests a preprogrammed set of muscle activity, potentially derived from the common drive suggested by De Luca and Mabrito.[42] The greater relative amount of VL activity in females during the LO phase may represent the combination of differences in preparatory and reactive VL activity.

Previous researchers have compared GMED and GMAX activation between males and females during single-leg squatting[32] and landing[31,48] tasks. We are unaware of any comparisons between gluteal muscle activation in males and females during cutting tasks. Therefore, we believe that we are the first to compare gluteal muscle activation amplitudes during side-step cutting between males and females. Contrary to our original hypothesis, we observed greater GMED activation in females during the LO phase of side-step cutting than in males. In addition, no sex differences in GMAX activation amplitude were noted. These findings were surprising considering that many authors[27,44,48–52] have reported greater knee valgus in females than in males. Several investigators have also reported no difference in GMED activation between males and females during single-leg squatting[32] and landing[31,48] tasks. Findings regarding GMAX activation are inconsistent. Like Zeller et al,[32] we found no difference between males and females. Zazulak et al,[31] however, reported decreased GMAX activity in females compared with males during the early deceleration phase of a single-leg landing. The differences in the tasks performed (cutting, squatting, and landing) among studies make it difficult to directly compare findings. Thus, the reason for the discrepancy in research findings surrounding GMED and GMAX activity is unclear.

In addition to the influence of sex, our findings also demonstrated that the type of cutting task performed and phase of contact have large effects on muscle activation amplitude and Q:H coactivation. We observed main effects for cutting task and phase of contact for the activation amplitude of all muscles tested and the Q:H coactivation ratio. The running-approach side-step cutting task resulted in greater activation amplitude for all muscles tested (approximately 29% more across all muscles), as well as higher Q:H coactivation ratios than for the box-jump side-step cutting task. Thus, the running-approach side-step cut appears to be a more demanding type of cutting task. However, the type of cutting task performed did not influence the ability to identify sex differences in muscle activation amplitude or Q:H coactivation, as we did not observe any sex-by-cutting task interactions. Therefore, sex differences in muscle activation amplitude and Q:H coactivation did not appear to be influenced by the nature of the side-step cutting task (running approach versus box-jump approach).

With the exception of the GMAX, muscle activation amplitude increased significantly from the PR to the LO phase of side-step cutting (approximately 34% more across all muscles, except GMAX). We hypothesize that increased activation amplitude during the LO phase was a result of the increased stability demands placed upon the lower extremity musculature during the weight-bearing phase of side-step cutting. Surprisingly, GMAX activation decreased (21%) from the PR to the LO phase of side-step cutting. We believe that the decrease in GMAX activation during the LO phase of side-step cutting underscores the importance of preparatory activation of this muscle to provide adequate frontal-plane and transverse-plane stability of the lower extremity during side-step cutting.

Clinical Relevance

The ACL is the primary restraint to anterior tibial translation induced by proximal anterior tibial shear forces,[10–16] but excessive lower extremity rotation[18–20,53] and knee valgus[53–55] also increase ACL loading. Although knee valgus and tibial rotation increase ACL loading, in vivo research clearly demonstrates that sagittal-plane mechanics are the dominant ACL loading mechanism.[18,20] Markolf et al[18] showed that isolated anterior tibial shear force generated ACL loading, but knee valgus and internal rotation moments could not generate ACL loading when applied in isolation. Knee valgus, varus, and internal rotation moments could only generate significant ACL loading when combined with anterior tibial shear force.[18] Berns et al[20] also demonstrated that neither pure knee internal-external rotation moment nor pure knee valgus-varus moment had effects on the strain of the anterior medial bundle of the ACL. Furthermore, isolated Q loading is capable of inducing ACL injury and rupture in cadaveric models.[43] These findings indicate that multiplanar loading facilitates the greatest ACL loading. However, sagittal-plane mechanics (eg, Q contraction, H contraction, and anterior tibial shear force) appear to be the major contributors to ACL loading, as knee valgus, varus, and internal rotation moments may only increase ACL loading when applied in combination with an anterior tibial shear force. Our findings of increased VL activation combined with greater Q:H coactivation ratios suggest that female soccer athletes may use a muscle activation pattern that may facilitate ACL loading.

Proximal anterior tibial shear force induced by the quadriceps may be a major factor in noncontact ACL injury.[56] This hypothesis is supported by research that consistently demonstrates an increase in ACL loading with Q contraction.[10–16,43] We believe that greater VL activation during the PR phase indicates that female soccer athletes use a preprogrammed motor control strategy to facilitate VL activation. Sex differences in VL activation were magnified during the LO phase, as female soccer athletes demonstrated 40% more VL activation than males immediately after foot contact with the ground. Noncontact ACL injury reportedly occurs immediately after foot contact with the ground during tasks requiring rapid deceleration or directional changes.[37,57] We defined the LO phase as the first 50% of the stance during the side-step cutting tasks, which encompasses the time period during which noncontact ACL injury is described to occur. Increased VL activity during the LO phase may result in greater anterior tibial shear forces when females are undergoing rapid deceleration and a directional change.

Quadriceps-induced ACL loading may be minimized by H muscle cocontraction.[14,16,21–23] Quadriceps-hamstrings coactivation enhances knee joint stability in both the sagittal and transverse planes by increasing joint stiffness, presumably limiting the force imparted on the ACL.[58–60] However, female soccer athletes did not demonstrate greater H activation than male soccer athletes. These findings suggest that female soccer athletes displayed a Q-dominant muscle activation strategy and that the greater Q:H coactivation ratio observed in females (Figure 6) was due to increased Q activation and not decreased H activation. Exercises to decrease Q:H coactivation ratios after foot contact with the ground may be effective injury-prevention techniques to reduce the risk of ACL injury in females. Future researchers should investigate the effects of preventive exercise interventions on Q:H coactivation ratios.

Limitations

Muscle activation measured during dynamic tasks is not the same as muscle force production. Muscle force is influenced by muscle activation, as well as muscle length and contractile velocity. Thus, if sex differences in muscle activation resulted in greater ACL loading is unknown. Increased Q:H coactivation ratios suggest that females may use muscle activation patterns that facilitate ACL loading by generating Q-induced anterior tibial shear forces. Future investigations to measure Q:H coactivation ratios, proximal anterior tibial shear forces, and ACL loading are needed to better understand the influence of Q:H coactivation on ACL loading during functional tasks associated with ACL injury.

We investigated male and female soccer athletes at the NCAA Division I level. Sex differences in neuromuscular factors may be influenced by skill level, training level, previous experience, age, and sport participation. Our findings are thus limited to NCAA Division I soccer athletes, as different results may occur when investigating different groups of males and females. Although our findings are limited to NCAA Division I soccer athletes, we believe these findings have substantial clinical relevance, as female collegiate soccer athletes have been shown to be at the highest risk for ACL injury.[9] Our demonstration of greater VL activation and Q:H coactivation ratios may lend insight into understanding potential ACL injury risk factors in female soccer athletes.

Given the inherent variability of EMG data, it is possible that our statistical power may have been limited due to sample size (20 males, 20 females). In particular, the increased variability associated with the LH and GMAX activation amplitude data may have affected the statistical power for these variables. However, the effect of sex on LH and GMAX activation amplitude appears to have been small based on the small η_p^2 values (see Results section) reported for these muscles, which calls into question whether or not a larger sample size would change these findings. Another potential limitation for the GMAX activation amplitude data was the MVIC testing methods. To avoid direct contact over the H EMG electrodes, we had the participant's knee in full extension and placed resistance over the popliteal fossa as he or she performed the MVIC into hip extension. This was done to prevent the H electrodes from shifting on the skin during GMAX MVIC testing. Performing the MVIC for the GMAX with the knee extended may have influenced the activation amplitude of this muscle, which may have affected our findings. However, we do not believe that this potential limitation altered our findings, as all participants were tested under identical conditions, allowing for a valid reference contraction for each volunteer that can be used to standardize dynamic EMG amplitudes. Furthermore, we are unaware of any published research demonstrating that GMAX activation amplitude during hip extension is influenced by knee flexion position.

CONCLUSIONS

We compared Q, H, GMED, and GMAX activation amplitude during running and box-jump side-step cutting tasks between male and female soccer athletes at the NCAA Division I level. Our results indicate that female soccer athletes used greater VL activation and Q:H coactivation ratios than males during the PR and LO phases of both cutting tasks. In addition, females demonstrated greater GMED activation during the LO phase of side-step cutting than males. No differences were noted, however, in RF, H, or GMAX activation amplitude between male and female soccer athletes. These findings indicate that female soccer athletes used a Q-dominant recruitment pattern during the side-step cutting tasks, whereas male soccer athletes employed a more balanced activation pattern between the Q and H. Vigorous Q contraction that is not offset by appropriate scaling of the H is known to facilitate anterior tibial translation and increase ACL loading. We theorize that greater VL activation and Q:H coactivation ratios may be a risk factor for ACL injury in female soccer athletes. Also, female soccer athletes used greater GMED activation during weight bearing, which may explain why previous researchers investigating knee valgus angle in soccer athletes have not observed sex differences in knee valgus angle.[30] Injury prevention programs designed to facilitate a more balanced Q:H coactivation ratio may reduce the risk of ACL. Whether or not increased VL activation and Q:H coactivation ratios actually place the ACL at greater risk for injury is unknown and requires further study.

REFERENCES

1. Arendt EA, Agel J, Dick R. Anterior cruciate ligament injury patterns among collegiate men and women. *J Athl Train.* 1999;34(2):86–92.

2. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. *Am J Sports Med.* 1995;23(6):694–701.
3. Bjordal JM, Arnly F, Hannestad B, Strand T. Epidemiology of anterior cruciate ligament injuries in soccer. *Am J Sports Med.* 1997;25(3):341–345.
4. Engstrom B, Johansson C, Tornkvist H. Soccer injuries among elite female players. *Am J Sports Med.* 1991;19(4):372–375.
5. Gwinn DE, Wilckens JH, McDevitt ER, Ross G, Kao T. The relative incidence of anterior cruciate ligament injury in men and women at the United States Naval Academy. *Am J Sports Med.* 2000;28(1):98–102.
6. Gomez E, DeLee JC, Farney WC. Incidence of injury in Texas girls' high school basketball. *Am J Sports Med.* 1996;24(5):684–687.
7. Malone TR, Hardaker WT, Garrett WE, Feagin JA, Bassett FH. Relationship of gender to anterior cruciate ligament injuries in intercollegiate basketball players. *J South Orthop Assoc.* 1993;2(1):36–39.
8. Messina DF, Farney WC, DeLee JC. The incidence of injury in Texas high school basketball: a prospective study among male and female athletes. *Am J Sports Med.* 1999;27(3):294–299.
9. Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in National Collegiate Athletic Association basketball and soccer: a 13-year review. *Am J Sports Med.* 2005;33(4):524–530.
10. Beynnon BD, Fleming BC, Johnson RJ, Nichols CE, Renstrom PA, Pope MH. Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. *Am J Sports Med.* 1995;23(1):24–34.
11. Durselen L, Claes L, Kiefer H. The influence of muscle forces and external loads on cruciate ligament strain. *Am J Sports Med.* 1995;23(1): 129–136.
12. Fleming BC, Renstrom PA, Ohlen G, et al. The gastrocnemius is an antagonist of the anterior cruciate ligament. *J Orthop Res.* 2001;19(6): 1178–1184.
13. Hirokawa S, Solomonow M, Lu Y, Lou ZP, D'Ambrosia R. Anterior-posterior and rotational displacement of the tibia elicited by quadriceps contraction. *Am J Sports Med.* 1992;20(3):299–306.
14. Li G, Rudy TW, Sakane R, Kanamori A, Ma CB, Woo SL. The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. *J Biomech.* 1999;32(4):395–400.
15. Markolf KL, Gorek JF, Kabo JM, Shapiro MS. Direct measurement of resultant forces in the anterior cruciate ligament: an in vitro study performed with a new experimental technique. *J Bone Joint Surg Am.* 1990; 72(4):557–567.
16. Renstrom P, Arms SW, Stanwyck TS, Johnson RJ, Pope MH. Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *Am J Sports Med.* 1986;14(1):83–87.
17. Bendjaballah MZ, Shirazi-Adl A, Zukor DJ. Finite element analysis of human knee joint in varus-valgus. *Clin Biomech (Bristol, Avon).* 1997; 12(3):139–148.
18. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res.* 1995;13(6):930–935.
19. Arms SW, Pope MH, Johnson RJ, Fischer RA, Arvidsson I, Eriksson E. The biomechanics of anterior cruciate ligament rehabilitation and reconstruction. *Am J Sports Med.* 1984;12(1):8–18.
20. Berns GS, Hull ML, Patterson HA. Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. *J Orthop Res.* 1992;10(2):167–176.
21. Draganich LF, Jaeger RJ, Kralj AR. Coactivation of the hamstrings and quadriceps during extension of the knee. *J Bone Joint Surg Am.* 1989; 71(7):1075–1081.
22. Pandy MG, Shelburne KB. Dependence of cruciate-ligament loading on muscle forces and external load. *J Biomech.* 1997;30(10):1015–1024.
23. Shelburne KB, Pandy MG. Determinants of cruciate-ligament loading during rehabilitation exercise. *Clin Biomech (Bristol, Avon).* 1998;13(6): 403–413.
24. Gottschalk F, Kourosh S, Leveau B. The functional anatomy of the tensor fascia latae and gluteus medius and minimus. *J Anat.* 1989;166:179–189.
25. Hase K, Stein RB. Turning strategies during human walking. *J Neurophysiol.* 1999;81(6):2914–2922.
26. Krebs DE, Robbins CE, Lavine L, Mann RW. Hip biomechanics during gait. *J Orthop Sports Phys Ther.* 1998;28(1):51–59.
27. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech (Bristol, Avon).* 2001;16(5):438–445.
28. Myer GD, Ford KR, Hewett TE. The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *J Electromyogr Kinesiol.* 2005;15(2):181–189.
29. Padua DA, Carcia CR, Arnold BL, Granata KP. Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. *J Mot Behav.* 2005;37(2):111–125.
30. Sigward SM, Powers CM. The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. *Clin Biomech (Bristol, Avon).* 2006;21(1):41–48.
31. Zazulak BT, Ponce PL, Straub SJ, Medvecky MJ, Avedisian L, Hewett TE. Gender comparison of hip muscle activity during single-leg landing. *J Orthop Sports Phys Ther.* 2005;35(5):292–299.
32. Zeller BL, McCrory JL, Kibler WB, Uhl TL. Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *Am J Sports Med.* 2003;31(3):449–456.
33. Kleissen RF. Effects of electromyographic processing methods on computer-averaged surface electromyographic profiles for the gluteus medius muscle. *Phys Ther.* 1999;70(11):716–722.
34. LeVeau B, Andersson G. Interpretation of the electromyographic signal. In: Soderberg G, ed. *Selected Topics in Surface Electromyography for Use in the Occupational Setting: Expert Perspectives.* Atlanta, GA: U.S. Department of Health and Human Services; 1992:70–95.
35. Blackburn JT, Riemann BL, Padua DA, Guskiewicz KM. Sex comparison of extensibility, passive and active stiffness of the knee flexors. *Clin Biomech (Bristol, Avon).* 2004;19(1):36–43.
36. Blackburn JT, Mynark RG, Padua DA, Guskiewicz KM. Influences of experimental factors on spinal stretch reflex latency and amplitude in the human triceps surae. *J Electromyogr Kinesiol.* 2006;16(1):42–50.
37. Boden BP, Dean GS, Feagin JA, Garrett WE. Mechanisms of anterior cruciate ligament injury. *Orthopedics.* 2000;23(6):573–578.
38. Padua DA, Arnold BL, Perrin DH, Gansndeder BM, Carcia CR, Granata KP. Fatigue, vertical leg stiffness, and stiffness control strategies in males and females. *J Athl Train.* 2006;41(3):294–304.
39. Urabe Y, Kobayashi R, Sumida S, et al. Electromyographic analysis of the knee during jump landing in male and female athletes. *Knee.* 2005; 12(2):129–134.
40. Mihata LC, Beutler AI, Boden BP. Comparing the incidence of anterior cruciate ligament injury in collegiate lacrosse, soccer, and basketball players: implications for anterior cruciate ligament mechanism and prevention. *Am J Sports Med.* 2006;34(6):899–904.
41. Withrow TJ, Huston LJ, Wojtys EM, Ashton-Miller JA. The relationship between quadriceps muscle force, knee flexion, and anterior cruciate ligament strain in an in vitro simulated jump landing. *Am J Sports Med.* 2006;34(2):269–274.
42. De Luca C, Mambrito B. Voluntary control of motor units in human antagonist muscles: coactivation and reciprocal activation. *J Neurophysiol.* 1987;58(3):525–542.
43. DeMorat G, Weinhold P, Blackburn JT, Chudik S, Garrett WE. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *Am J Sports Med.* 2004;32(2):477–483.
44. McLean SG, Lipfert SW, van den Bogert AJ. Effect of gender and defensive opponent on the biomechanics of sidestep cutting. *Med Sci Sports Exerc.* 2004;36(6):1008–1016.
45. Decker MJ, Torry MR, Wyland DJ, Sterett WI, Steadman JR. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech (Bristol, Avon).* 2003;18(7):662–669.
46. Salci Y, Kentel BB, Heycan C, Akin S, Korkusuz F. Comparison of landing maneuvers between male and female college volleyball players. *Clin Biomech (Bristol, Avon).* 2004;19(6):622–628.
47. Lephart SM, Ferris CM, Riemann BL, Myers JB, Fu FH. Gender differences in strength and lower extremity kinematics during landing. *Clin Orthop Relat Res.* 2002;401:162–169.
48. Russell KA, Palmieri RM, Zinder SM, Ingersoll CD. Sex differences in

valgus knee angle during a single-leg drop jump. *J Athl Train.* 2006; 41(2):166–171.
49. McLean SG, Walker KB, Van Den Bogert AJ. Effects of gender on lower extremity kinematics during rapid direction changes: an integrated analysis of three sports movements. *J Sci Med Sport.* 2005;8(4):411–422.
50. Yu B, McClure SB, Onate JA, Guskiewicz KM, Kirkendall DT, Garrett WE. Age and gender effects on lower extremity kinematics of youth soccer players in a stop-jump task. *Am J Sports Med.* 2005;33(9):1356–1364.
51. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc.* 2003;35(10):1745–1750.
52. Ford KR, Myer GD, Toms HE, Hewett TE. Gender differences in the kinematics of unanticipated cutting in young athletes. *Med Sci Sports Exerc.* 2005;37(1):124–129.
53. Fung DT, Zhang LQ. Modeling of ACL impingement against the intercondylar notch. *Clin Biomech (Bristol, Avon).* 2003;18(10):933–941.
54. Fukuda Y, Woo SL, Loh JC, et al. A quantitative analysis of valgus torque on the ACL: a human cadaveric study. *J Orthop Res.* 2003;21(6):1107–1112.
55. Matsumoto H, Suda Y, Otani T, Niki Y, Seedhom BA, Fujikawa K. Roles of the anterior cruciate ligament and the medial collateral ligament in preventing valgus instability. *J Orthop Sci.* 2001;6(1):28–32.
56. Hewett TE, Shultz SJ, Griffin LY, eds. *Understanding and Preventing Noncontact ACL Injuries.* Champaign, IL: Human Kinetics; 2007:141–153.
57. Boden BP, Griffin LY, Garrett WE. Etiology and prevention of noncontact ACL injury. *Physician Sportsmed.* 2000;28(4)53–60.
58. Wojtys EM, Huston LJ, Schock HJ, Boylan JP, Ashton-Miller JA. Gender differences in muscular protection of the knee in torsion in size-matched athletes. *J Bone Joint Surg Am.* 2003;85(5):782–789.
59. Wojtys EM, Ashton-Miller JA, Huston LJ. A gender-related difference in the contribution of the knee musculature to sagittal-plane shear stiffness in subjects with similar knee laxity. *J Bone Joint Surg Am.* 2002;84(1): 10–16.
60. MacWilliams BA, Wilson DR, DesJardins JD, Romero J, Chao EY. Hamstrings cocontraction reduces internal rotation, anterior translation, and anterior cruciate ligament load in weight-bearing flexion. *J Orthop Res.* 1999;17(6):817–822.

Ashley M. Hanson, MA, ATC, contributed to conception and design; acquisition and analysis and interpretation of the data; and drafting, critical revision, and final approval of the article. Darin A. Padua, PhD, ATC; J. Troy Blackburn, PhD, ATC; William E. Prentice, PhD, PT, ATC; and Christopher J. Hirth, PT, ATC, contributed to conception and design; analysis and interpretation of the data; and drafting, critical revision, and final approval of the article.

Address correspondence to Darin A. Padua, PhD, ATC, University of North Carolina, 216 Fetzer, CB#8700, Chapel Hill, NC 27599-8700. Address e-mail to dpadua@email.unc.edu.