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The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting

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Abstract

Background. It has been suggested that gender differences in the performance of athletic maneuvers is a contributory factor with respect to the disproportionate incidence of non-contact anterior cruciate ligament injury in female athletes. The purpose of this study was to evaluate gender differences in knee joint kinematics, kinetics and muscle activation during a side-step cutting.

Methods. Three-dimensional kinematics, ground reaction forces (2400 Hz) and electromyographic activity (surface electrodes) were recorded during the early deceleration phase of side-step cutting in 30 healthy collegiate soccer players (15 male, 15 female). Gender differences in knee joint kinematics, peak moments, net joint moment impulse and average muscle EMG intensity were evaluated with one-tailed *t*-tests.

Findings. No differences in kinematics were found. However, when compared to males, females demonstrated a smaller peak knee flexor moment (1.4 (0.8) vs. 2.1 (0.8) N m/kg, $P = 0.05$) and a greater knee adductor moment (0.43 (0.5) vs. 0.01 (0.3) N m/kg, $P < 0.01$) during early deceleration. In addition, females displayed greater average quadriceps EMG intensity than males (191% vs. 151% maximum voluntary isometric contraction, $P = 0.02$).

Interpretation. In general, females experienced increased frontal plane moments and decreased sagittal plane moments during early deceleration. These differences are suggestive of an "at risk" pattern in that frontal plane support of the knee is afforded primarily by passive structures (including the anterior cruciate ligament). Furthermore, increased quadriceps activity and smaller net flexor moments may suggest less sagittal plane protection (i.e., increased tendency towards anterior tibial translation).
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Keywords: ACL; Knee; Gender difference

1. Introduction

Studies comparing injury rates between males and females participating in the same sport have shown a greater incidence of anterior cruciate ligament (ACL) injuries in female athletes (Arendt and Dick, 1995; Malone et al., 1993; McNair et al., 1990). For example, assessment of ACL injuries in 893 men's and women's National Collegiate Athletic Association (NCAA) soccer and basketball programs from 1989 to 1993 found the rate of ACL injury per exposure for female athletes was greater than that of their male counterparts (2.8 and 4.1 times, respectively) (Arendt and Dick, 1995). More recent figures reported by the NCAA (1994–1998) have shown that this trend is continuing (Arendt et al., 1999).

While an ACL injury can be a result of contact with another player or object, it has been reported that ≈70% of ACL injuries result from situations that do not involve contact (Boden et al., 2000; McNair et al., 1990). From a qualitative standpoint, one mechanism of a non-contact ACL injury has been described as occurring

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just after foot contact during a maneuver that includes a sharp deceleration and change in direction, i.e., cutting or landing from a jump (Boden et al., 2000). At this point, the knee has been described to be in a position of internal rotation, valgus, and relative extension (i.e., 0–30°) (Kirkendall and Garrett, 2000). Data from in vitro studies appear to be consistent with observed mechanisms of ACL injury demonstrating that the ACL is loaded in these positions (Durselen et al., 1995; Markolf et al., 1990, 1995).

Several studies have evaluated gender related differences in performance of athletic tasks with mixed results. In regard to kinematics, females have been found to demonstrate greater knee valgus (Malinzak et al., 2001; McLean et al., 1999) and smaller knee flexion angles (Malinzak et al., 2001; Decker et al., 2002; Lephart et al., 2002) than males during cutting and landing tasks, however, these findings are not consistent across studies (Cowling and Steele, 2001; Pollard et al., 2004). Similarly, studies evaluating knee joint kinetics also have reported conflicting results. For example, subject specific modeling of a side-step cutting task revealed that females demonstrated greater valgus and lower internal rotation torques at the knee when compared to males (McLean et al., 2004), yet similar experimental data found no gender difference in knee kinetics (Pollard et al., 2004).

Evaluation of muscle activation patterns using electromyography (EMG) suggests that females demonstrate greater quadriceps and less hamstring activity than males during cutting (Malinzak et al., 2001). While these studies have provided important information about gender differences during sport specific tasks, a comprehensive evaluation of knee joint kinematics, kinetics and muscle activation patterns has not been performed. Given that each of these components are likely important aspects of the mechanism of ACL injury, such an investigation is needed to better understand injurious movement patterns that could put females at greater risk.

The purpose of this study was to evaluate gender differences in knee joint kinematics, kinetics and muscle activation during side-step cutting. Based on previous literature in this area it was hypothesized that when compared to males, females would demonstrate: (1) reduced knee flexion and greater knee valgus, (2) greater frontal and transverse plane moments at the knee and (3) increased activation of the quadriceps and decreased activation of the hamstrings. Information from this study will be useful in determining whether females perform this maneuver differently than their male counterparts and whether they perform it in a manner that is suggestive of increased risk for ACL injury.

2. Methods

2.1. Subjects

Thirty soccer players (15 males and 15 females) between the ages of 18 and 27, participated in this study (Table 1). Subjects were NCAA Division I or II athletes with at least 1 year of collegiate experience. The average years of soccer experience for the females and males in this study was 13.4 (2.2) yr and 12.4 (3.0) yr, respectively. Twenty seven of the 30 subjects reported that they were right limb dominant. One male and one female subject reported left limb dominance and one female subject could not identify a dominant leg. Limb dominance was determined by asking the athlete which leg they could kick a ball furthest with.

All subjects were healthy with no current complaints of lower extremity injury. Subjects were excluded from the study if they reported any of the following: (1) history of previous ACL injury or repair (2) previous injury that resulted in ligamentous laxity at the ankle, hip or knee, or (3) presence of any medical or neurologic condition that would impair their ability to perform a side-step cutting task.

2.2. Instrumentation

Three-dimensional motion analysis was performed using a computer aided video, 6-camera (Vicon) motion analysis system (Oxford Metrics Ltd., Oxford, England). Kinematic data were sampled at 120 Hz and recorded digitally on dual Pentium III 1 GHz personal computer. Cameras were positioned to so that each marker was de-

Table 1
Subject characteristics

	Males ($n = 15$)			Females ($n = 15$)		
	Mean	SD	Range	Mean	SD	Range
Age (yr)	19.6	1.9	18–26	19.4	1.5	18–23
Height (cm)*	179.1	6.0	167–185	167.4	8.0	154–180
Weight (kg)*	74.2	7.0	63.6–85.5	65.9	7.0	51.4–82.9
BMI (kg/m^2)	23.1	1.7	19.8–25.9	23.5	1.6	20.9–26.3
Soccer experience (yr)	12.4	3.0	6–15	13.4	2.2	8–16

* Indicates males greater than females ($P < 0.05$).

tected by at least two cameras throughout the task (Fig. 1). Reflective markers (25 mm spheres) placed on specific boney landmarks (see below) where used to calculate motion of the pelvis, hip, knee and ankle in the sagittal, frontal and transverse planes.

Ground reaction forces where collected using a calibrated and leveled AMTI force plate (Model#OR6-6-1, Newton, MA, USA) embedded in the floor at a rate of 2400 Hz. EMG activity of the vastus lateralis and of the medial and lateral hamstring muscles were recorded at 2400 Hz, using pre-amplified bipolar, surface electrodes (Motion Control, Salt Lake City, UT, USA). EMG signals were telemetered to a 12-bit analog to digital converter using an FM-FM telemetry unit. Differential amplifiers were used to reject the common noise and amplify the remaining signal (gain = 1000).

Every attempt was made to minimize marker movement inherent to the motion analysis system and marker set. Between day reliability ($n = 5$) was assessed during the cutting maneuver described above was determined to be acceptable with fair coefficient of multiple correlation (CMC) values for sagittal, frontal and transverse plane knee kinematics (0.98, 0.63, and 0.61, respectively). Excellent repeatability for knee joint moment calculations in the sagittal, frontal and transverse planes (0.93, 0.90, and 0.93, respectively) were observed. These results are consistent with those reported for gait data using a similar marker set and system (Kadaba et al., 1989).

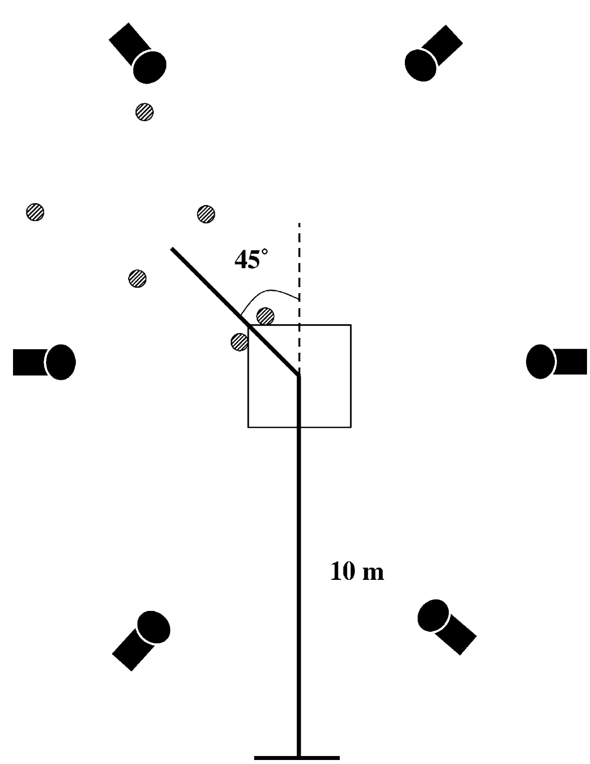

Fig. 1. Experimental set-up. Subjects contacted the force plate with their right foot and changed direction to the left. A series of cones set at 35° and 55° from the original direction guided the subjects to perform a 45° cut.

2.3. Procedures

All testing took place at the Musculoskeletal Biomechanics Research Laboratory at the University of Southern California. Prior to participation, all procedures were explained to each subject and informed consent was obtained as approved by the Institutional Review Board for the University of Southern California Health Sciences Campus.

Prior to testing, each subjects' skin was shaved and cleaned with alcohol. Surface EMG electrodes were then placed over the quadriceps (vastus lateralis), lateral hamstrings (biceps femoris) and medial hamstrings (semimebranosis and semitendinosis) of the right leg in accordance with procedures described by Cram et al. (1998). These muscles were chosen to represent the knee flexors and extensors. Electrodes were secured with tape and an elastic sleeve to minimize motion artifact. The EMG telemetry unit was worn in a pack secured to the subject's back.

To allow for comparison of EMG intensity between subjects and muscles, and to control for variability induced by electrode placement, EMG obtained during the cutting maneuver was normalized to the EMG acquired during a maximal voluntary isometric contraction (MVIC). Uniform testing positions were used to ensure reproducible isometric contractions in positions that allowed for the generation of maximum EMG signal output. The MVIC test for the quadriceps was performed with the subject seated (hip and knee flexed to 90° and 60°, respectively), and pushing against a fixed resistance. The MVIC for the medial and lateral hamstrings was performed in supine with the hip and knee flexed to 30°. A strap was secured to the table and placed around the subject's hips which allowed them to perform a single leg bridge (i.e., resisting hip extension with the knee flexed). Subjects performed one MVIC for each muscle group tested, and each contraction was held for 6 s. There was a 6 s rest period between tests.

Following MVIC testing, reflective markers were placed on the following anatomical landmarks: bilateral anterior superior iliac spines, posterior superior iliac spines, lateral epicondyles of the knee, lateral malleoli, calcaneus, and bases of the fifth metatarsal (Kadaba et al., 1989). The thigh and calf markers were mounted on 5 cm wands and secured on the thigh and shank with elastic bands. The foot markers were placed on the shoes. To control for the potential influence of varying footwear, subjects were fitted with same style of cross-training shoe (New Balance Inc., Boston, MA, USA).

Each participant performed four trials of a side-step cutting maneuver as previously described by McLean et al. (1999). Subjects were instructed to run five meters at a speed of 5.5–7.0 m/s before contacting their right foot on the force plate and then change direction to the left. Cones placed at 35° and 55° from the original direction of progression were used to direct the subjects to cut at an angle of 45° (Fig. 1). Approach speed was calculated with the use of a photoelectric switch and force plate contact. The trial was considered acceptable if the subject landed on the force plate at the pre-determined speed. Practice trials allowed the subjects to become familiar with the procedures and instrumentation.

2.4. Data analysis

Vicon Clinical Manager (VCM) software (Oxford Metrics Ltd.) was used to quantify lower extremity motion and moments in the sagittal, frontal and transverse planes. Kinematic data was filtered using a Woltering quintic spline filter with a predicted mean square error of 20 mm. Net joint moments were calculated with standard inverse dynamics equations. Net joint moment impulse was calculated as the integral of the net joint moment over time. To facilitate comparison of moment data between groups, all kinetic data were normalized to body mass.

Raw EMG data were filtered with a band pass Butterworth filter (20–500 Hz) with a roll off of 5 and a 60 Hz notch filter. Full wave rectification and smoothing of the EMG signal was accomplished using root-mean-square (RMS) values over a 75 ms interval.

The processed EMG signal from each MVIC trial was averaged over 1-s intervals, with the greatest 1-s average being used for normalization purposes. EMG collected from the cutting trials were expressed as a percentage of the EMG obtained during MVIC (% MVIC).

All data were normalized to 100% of the cut cycle. The cut cycle was identified as the period from initial contact of the right foot to toe off, as determined by the force plate recordings. For the purposes of this study, only the early deceleration phase of the cutting cycle was considered as this is the time in which the majority of non-contact ACL injuries have been reported to occur (Boden et al., 2000). Early deceleration was defined as the first 20% of the cut cycle; the time in which the knee is in less than 40° of flexion (Boden et al., 2000).

The dependent variables evaluated in this study included knee joint kinematics and kinetics (moment and moment impulse) in the sagittal, frontal and transverse planes as well as EMG intensity of the quadriceps, medial and lateral hamstrings during the early deceleration phase of the cutting task. As there were no distinct peaks in knee joint kinematics during early deceleration, the average angle was calculated to describe knee joint position during this phase. Knee joint kinetics were assessed by evaluating the peak joint moments and net joint moment impulse during early deceleration. Average normalized EMG intensity was used to characterize the contributions of the selected muscles to the knee joint moments and kinematics during this phase. For each subject, all dependent variables represented the mean of the four trials collected.

2.5. Statistical analysis

To account for the relationship among the variables being evaluated, each was categorized based on the concept or construct that they represented: kinematics, peak moments, impulse and EMG. Multivariate Hotelling's T^2 tests were to determine whether differences existed between genders for any of the variables within a particular group. In the case of a significant Hotelling's test, one-tailed, independent samples t-tests were performed to determined which variables were significantly different between groups. Statistical analyses were performed using SPSS statistical software. Significance levels where set at $P \leqslant 0.05$.

3. Results

The average approach speed for males and females was 5.8 (0.4) ms and 5.7 (0.4) ms, respectively and did not differ between groups ($P = 0.5$).

3.1. Kinematics

There were no significant differences in average sagittal plane knee kinematics between males and females during early deceleration ($P = 0.18$; Fig. 2a). This finding also was consistent for the frontal and transverse planes ($P = 0.14$ and 0.12, respectively; Fig. 2b and c).

3.2. Kinetics

During early deceleration, males demonstrated a significantly greater peak knee flexor moment than females (2.1 (0.8) vs. 1.4 (0.7) N m/kg-Bwt; $P = 0.025$; Fig. 3b). On average, females demonstrated a greater initial peak adductor moment (valgus) than males (−0.43 (0.5) vs. 0.006 (0.3) N m/kg-Bwt; $P = 0.005$; Fig. 3a). In regards to peak transverse plane moments, there were no significant differences found between males and females ($P = 0.4$; Fig. 3c).

When compared to female athletes, male athletes demonstrated larger sagittal plane net joint moment impulse at the knee during early deceleration (0.06 (0.02) vs. 0.04 (0.02) N ms/kg-Bwt; $P < 0.01$; Fig. 4a). No significant differences were found in the net joint moment

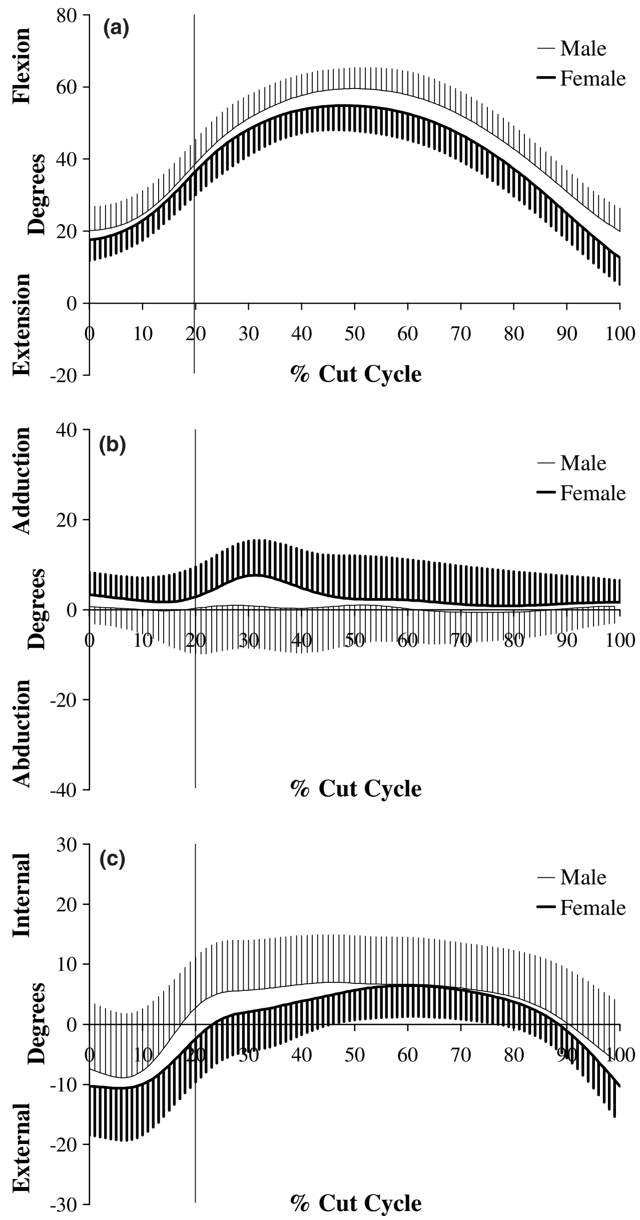

Fig. 2. Comparison of knee joint kinematics between males and females in the (a) sagittal, (b) frontal and (c) transverse planes during side-step cutting. Vertical line indicates end of early deceleration phase. No group differences were observed. Error bars equal 1 standard deviation.

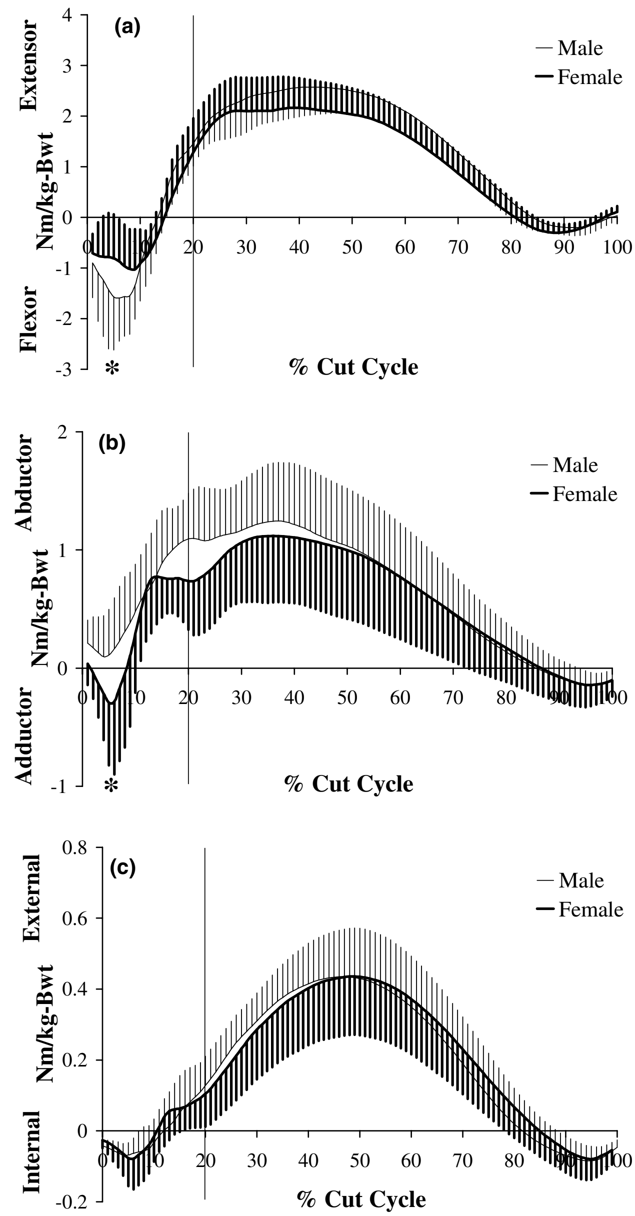

Fig. 3. Comparison of knee joint moments between males and females in the (a) sagittal, (b) frontal and (c) transverse planes during side-step cutting. Vertical line indicates end of early deceleration phase. * indicates significant gender differences ($P < 0.05$). Error bars equal 1 standard deviation.

impulse in the frontal and transverse planes ($P = 0.18$ and 0.26, respectively; Fig. 4b and c).

3.3. Muscle EMG intensity

During early deceleration, female subjects demonstrated greater average quadriceps EMG than males (191 vs. 151% MVIC, $P = 0.02$; Fig. 5a). There were no significant differences in average EMG of the medial or lateral hamstrings ($P = 0.17$ and 0.07, respectively; Fig. 5b and c).

4. Discussion

The results of this study found that gender differences exist while males and female perform a side-step cutting maneuver. While no gender differences in knee kinematics were observed, females demonstrated smaller sagittal plane moments and greater frontal plane moments than males during early deceleration. Additionally, when compared to males, females exhibited greater quadriceps activation.

With respect to knee kinetics, females demonstrated an average adductor (valgus) moment during early

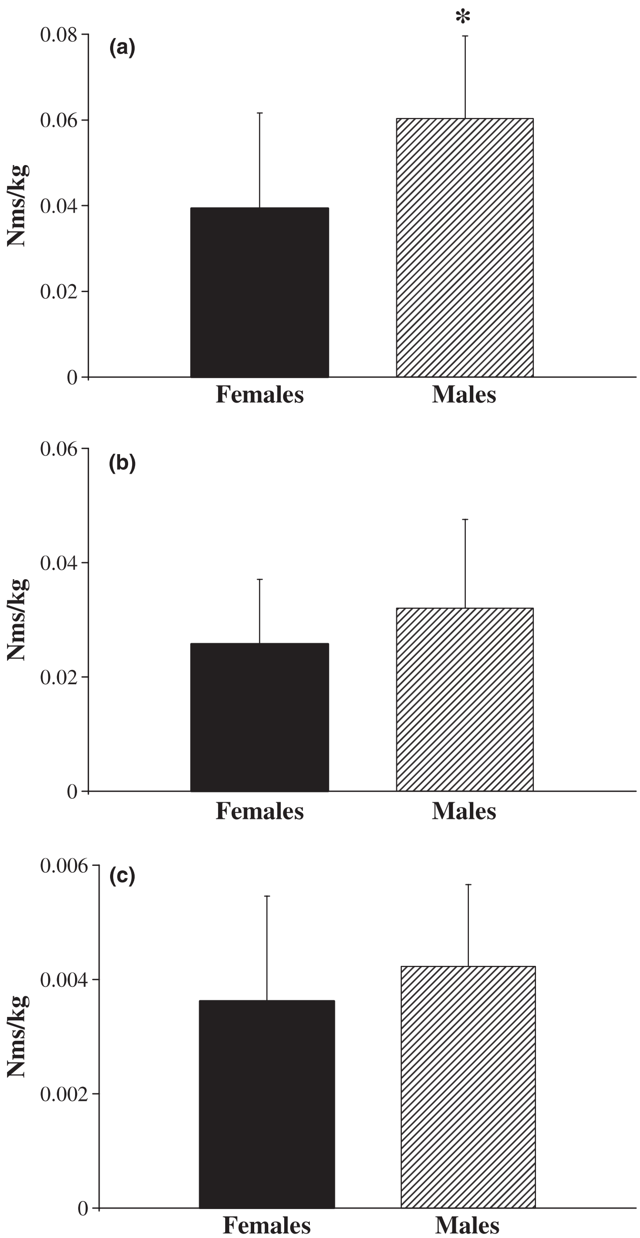

Fig. 4. Comparison of knee net joint moment impulse between the males and females in the (a) sagittal, (b) frontal and (c) transverse planes during early deceleration of side-step cutting. * indicates significant gender differences ($P < 0.05$). Error bars equal 1 standard deviation.

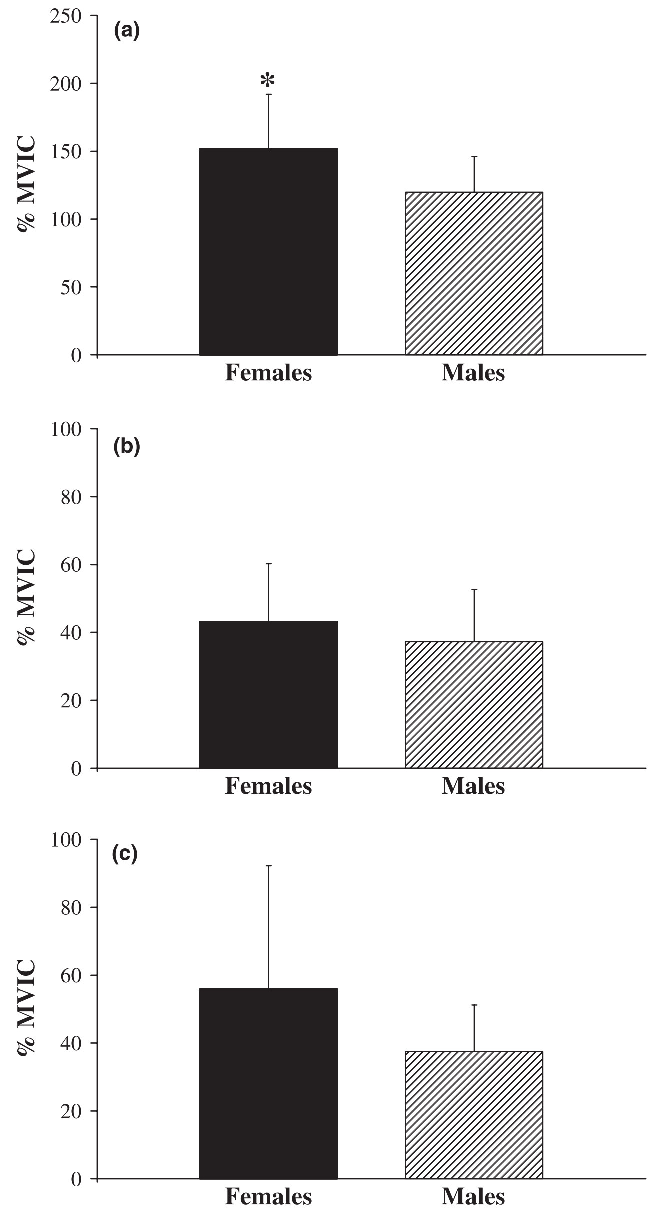

Fig. 5. Comparison between males and females of (a) quadriceps, (b) medial hamstring and (c) lateral hamstring EMG intensity during early deceleration of side-step cutting. * indicates significant gender differences ($P < 0.05$). Error bars equal 1 standard deviation.

deceleration, whereas the male subjects demonstrated an average abductor (varus) moment (Fig. 3b). These frontal plane differences become more apparent when the individual data were plotted in ascending order. As shown in Fig. 6, 80% of the females demonstrated an adductor (valgus) moment compared to only 40% of the males. On average, the females demonstrated peak frontal moments that were two times greater than their male counterparts. Although gender differences were evident in peak frontal plane moments, the net joint moment impulse did not differ between groups. These data indicate that, while there were no differences in overall load on the joint in the frontal plane, females demonstrated a different torque at the knee than their male counterparts (i.e., valgus vs. varus).

Our data support previous subject specific modeling work that found females demonstrated greater valgus moments during early stance of a similar side-step cutting task when compared to males (McLean et al., 2004). While previous work has reported frontal moment patterns with similar magnitude and timing (Pollard et al., 2004; McLean et al., 2004) this is the first this study to identify gender differences in knee valgus moments during side-step cutting. This finding is consid-

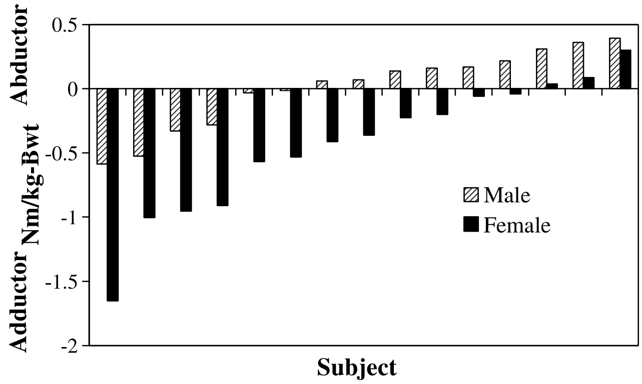

Fig. 6. Comparison of individual peak frontal plane moments displayed by males and females during early deceleration of side-step cutting. Each bar represents an individual subject.

ered important as frontal plane support of the knee is primarily afforded by passive structures including the ACL (Lloyd and Buchanan, 1996). Moreover, in vitro and modeling studies have found that an abductor (valgus) torque can increase the load on the ACL (Bendjaballah et al., 1997; Markolf et al., 1990, 1995), particularly at small knee flexion angles (Markolf et al., 1995). The fact that this gender difference in frontal plane loading occurred during early deceleration of the cut cycle when the knee is in minimum knee flexion (i.e., <40°) could be interpreted as "at risk" behavior.

With regards to peak sagittal plane moments, all subjects demonstrated a net knee flexor moment during early deceleration. However, the female athletes demonstrated a significantly smaller peak flexor moment and net joint moment impulse than the male athletes. This finding may be explained by the muscle activation pattern exhibited by the females during this phase. As the knee flexor moment represents the net joint moment in the sagittal plane (the sum of the flexor and extensor moments), the observed increase in knee extensor activity in the females could have resulted in an increase in the extensor moment, and in turn, a reduction of the net flexor moment. This muscle activation pattern supports the findings of Malinzak et al. (2001) who reported that females demonstrated greater quadriceps activity when compared to males during a side-step cutting task. Similarly, these authors found no difference in hamstring activity for males and females during the early portion of the stance phase of this task (Malinzak et al., 2001).

Previous authors have proposed that sagittal plane mechanisms including increased knee extensor moments and greater quadriceps to hamstring muscle activation patterns contribute to non-contact ACL injuries. For example, the anterior shear forces related to knee extensor moments, estimated from inverse dynamics calculations have been thought to result in anterior tibial translation and in turn increased ACL strain (Chappell et al., 2002). In addition, measures of ACL strain have revealed that isolated quadriceps force can increase the strain (DeMorat et al., 2004; Fleming et al., 2001; Markolf et al., 1990; Torzilli et al., 1994) and isolated hamstring force can decrease the strain of the ACL (Renstrom et al., 1986; Torzilli et al., 1994). While these mechanisms have been proposed to contribute to ACL injury (DeMorat et al., 2004), recent investigations modeling the contribution of quadriceps and hamstring muscle activation patterns in addition to external torques on sagittal plane loading have found that the forces were not large enough to result in an ACL injury (McLean et al., 2004). Thus, despite the similarities between our data and that of previous authors, it is unclear if these patterns would place the females at greater risk of ACL injury.

No gender differences were observed in the sagittal, transverse or frontal plane knee kinematics. This finding was not entirely surprising as previous studies evaluating gender differences in knee joint kinematics during similar side-step cutting tasks have reported inconsistent results. For example, McLean et al. (1999) and Malinzak et al. (2001) found that females demonstrated greater knee valgus angles than males during a side-step cutting task, however the differences reported by Malinzak and colleagues were ≈10° greater than those reported by McLean. A recent study evaluating gender differences during side-step cutting reported kinematic patterns similar to the current study, reported no gender differences in knee joint kinematics (Pollard et al., 2004). Given the high variability of frontal and transverse plane kinematics during this task in relation to a potentially small difference between genders much larger sample sizes would be needed to reach significance.

The varying kinematic results across studies may be attributed to the subjects studied. For example, studies reporting kinematics differences, evaluated recreational athletes and skilled athletes with varying years of experience (Malinzak et al., 2001; McLean et al., 1999). Similar to the work of Pollard et al. (2004), the population in the current study was comprised of college level soccer players with more experience. The fact that the current study did not find gender differences in kinematic patterns may be attributed to a more skilled, homogenous population.

While the results of this study provide evidence in support of the theory that females perform certain athletic maneuvers in a way that may predispose them to ACL injury, it should be noted that evaluation of individual data suggests that only a percentage of females may be considered "at risk". Some females demonstrated kinematic, kinetic and muscle activation patterns that were similar to that of males. In addition, since this study only evaluated high level collegiate athletes, an argument could be made that females who have successfully participated in high risk sports (such as soccer) for an extended period of time may represent a group of women who have found appropriate adaptive measures. Whether or not similar biomechanical patterns during side-step cutting would be evident in younger, less-skilled, populations remains to be seen.

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