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Neuromuscular and Lower Limb Biomechanical Differences Exist Between Male and Female Elite Adolescent Soccer Players During an Unanticipated Side-cut Maneuver

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Background: Female athletes are 2 to 8 times more likely than male athletes to injure the anterior cruciate ligament during a noncontact athletic maneuver. Identifying anterior cruciate ligament injury risk factors in female athletes may help with the development of preventive training programs aimed at reducing injury rates.

Hypothesis: Differences between genders in lower limb kinematics, kinetics, and neuromuscular patterns will be identified in an adolescent soccer population during an unanticipated side-cut maneuver.

Study Design: Controlled laboratory study.

Methods: Forty-two elite adolescent soccer players (21 male and 21 female) performed an unanticipated side-cut maneuver, with the 3-dimensional kinematic, kinetic, and electromyographic lower limb data being analyzed using principal component analysis.

Results: The female athletes had higher gastrocnemius activity, normalized to maximal voluntary isometric contractions, and a mediolateral gastrocnemius activation imbalance that was not present in the male athletes during early stance to midstance of the side-cut. Female athletes demonstrated greater rectus femoris muscle activity throughout stance, and the only hamstring difference identified was a mediolateral activation imbalance in male athletes only. Female athletes performed the side-cut with less hip flexion and more hip external rotation and also generated a smaller hip flexion moment compared with the male athletes.

Conclusion: This is the first study to identify gender-related differences in gastrocnemius muscle activity during an unanticipated cutting maneuver.

Clinical Relevance: The increased and imbalanced gastrocnemius muscle activity, combined with increased rectus femoris muscle activity and reduced hip flexion angles and moments in female subjects, may all have important contributing roles in the higher noncontact ACL injury rates observed in female athletes.

Keywords: anterior cruciate ligament injury; electromyography; gender; kinematics; kinetics; side-cut; unanticipated

The anterior cruciate ligament (ACL) of the knee has an important role in joint stability, particularly in resisting internal rotation and anterior translation of the tibia with respect to the femur.[33] Injury to the ACL can be detrimental to an athlete's career, often requires invasive surgery to repair, is 2 to 8 times more prevalent in women than men,[1,2] and also leads to accelerated osteoarthritic changes to the knee joint.[50] Although the ACL can be injured from a contact blow to the knee, 70% to 80% of the time this ligament is injured during a noncontact maneuver such as landing from a jump or cutting to quickly change directions[8,40] in sports like soccer, basketball, volleyball, and European handball.

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Comprehensive overview articles exist throughout the literature that summarize the numerous studies addressing noncontact ACL injury risk factors and the gender disparity associated with this injury.[20,22] Physiologic and biomechanical risk factors can potentially be controlled and altered to reduce this risk, but it is difficult to accurately measure these factors during sport-specific scenarios where ACL injuries occur. Measuring body positioning, joint loading, and neuromuscular coordination during athletic maneuvers in a laboratory setting offers great potential for capturing and understanding risk factors related to noncontact ACL injuries, particularly in female athletes.

Several studies focusing on the cutting-related maneuver[18,32,36-38,43,46] have analyzed combinations of lower limb kinematics, kinetics, and electromyography (EMG) in an attempt to identify ACL injury risk factors associated with female athletes. Although findings between studies vary, researchers have been able to identify gender-related differences in recreational, high school, or collegiate-level athletes during various phases of the cutting maneuver.

It has been demonstrated that contraction of the quadriceps muscle at knee flexion angles less than approximately 45° strains the ACL,[3,44] and hamstring muscle contraction in a flexed knee can help protect the ACL by reducing ligament strain in an agonist manner.[34,39,44] Activation patterns of the quadriceps and hamstring muscles have been compared between genders for preplanned athletic maneuvers, and differences have been detected. Malinzak et al[32] demonstrated greater quadriceps activation levels (vastus medialis [VM] and vastus lateralis [VL] averaged together), normalized to maximum voluntary contractions (MVC), in women compared with men during preplanned straight running and cutting maneuvers. Sigward and Powers[46] analyzed only the VL and not the VM and found that within the first 20% of the stance phase of a preplanned side-cut, the VL in teenage female soccer players was more activated than that of their male counterparts (191% MVC vs 151% MVC).

Gender differences in hamstring activity can vary between different athletic tasks. Malinzak et al[32] demonstrated that although female recreational athletes have significantly reduced hamstring activity (lateral hamstring [LH] and medial hamstring [MH] averaged together) during the stance portion of a preplanned straight run and cross-cut, for a side-cut maneuver these activation differences between genders are less evident. Sigward and Powers[46] analyzed a preplanned side-cut maneuver only, and gender differences in hamstring activity were not captured between the male and female subject groups.

The gastrocnemii, the third main muscle group crossing the knee, have received little attention with respect to cutting studies and the potential influence of this muscle group on the ACL. Studies using a computer-based model[41] and a differential variable transducer implanted on the ACL[17] have shown that contraction of the gastrocnemii alone or in combination with the quadriceps muscle is able to increase the load experienced by the ACL. No study has specifically evaluated gender differences for the gastrocnemii during cutting maneuvers, and identifying activation differences between men and women for this muscle group may provide valuable information related to the higher prevalence of ACL injuries in female athletes.

Kinematic comparisons of athletic maneuvers between genders are more plentiful than neuromuscular comparisons. Some of these studies have reported that female athletes side-cut with greater knee valgus[18,32,37,38] and smaller knee flexion angles[32,37] compared with male athletes, whereas other studies have found no knee kinematic differences between genders during a preplanned or unanticipated side-cut.[43,46] Gender differences in hip abduction, hip flexion, or ankle inversion have also been identified for the side-cut maneuver.[18,37]

Many studies have analyzed joint moments of the lower limb during side-cutting,[6,7,23,47] but only a select few have made gender comparisons of the moments.[43,46] Pollard et al[43] reported no gender differences in hip and knee moments, whereas Sigward and Powers[46] were able to demonstrate that women had smaller peak net internal knee flexion moments and greater net internal knee adductor moments during the first 20% of the side-cut stance phase.

Collectively, these studies have identified potential risk factors associated with the higher prevalence of ACL injuries in female athletes during cutting-related maneuvers. One of the main criticisms for most of these laboratory studies, however, is that the maneuvers analyzed may not adequately represent a true gamelike scenario where the ACL can be damaged from an unanticipated or perturbed noncontact maneuver. More recent laboratory studies have used light-guiding systems to more closely approximate a true gamelike situation by forcing the athlete to execute the cutting maneuver at the last possible moment.[5,6,18,23,43] Although it is difficult to assess exactly how well these unanticipated laboratory maneuvers replicate the true gamelike situation, Besier et al[5] were able to show in male athletes that unanticipated running and cutting maneuvers generate greater knee joint moments and muscle activation levels compared with similar but preplanned maneuvers. Adduction/abduction and internal/external rotation knee joint moments increased approximately 100% for the unanticipated cutting maneuvers, whereas muscle activations only showed a 10% to 20% increase. The authors also concluded that muscle activation patterns were more selective for the preplanned maneuvers, whereas for the unanticipated maneuvers, a more generalized co-contraction pattern was adopted for the musculature surrounding the knee.

Only a couple of studies have analyzed the biomechanics of the unanticipated side-cut with a focus on differences between genders.[18,43] None of these studies simultaneously compared the kinematics and kinetics of the knee, hip, and ankle along with the neuromuscular response of the muscles surrounding the knee during the unanticipated side-cut maneuver. As well, previous cutting studies have compared discrete waveform measures and have not made group comparisons based on features identified using the entire waveform during stance.

Traditionally, biomechanical and neuromuscular waveforms have been analyzed by subjectively defining and extracting parameters describing discrete instants or events associated with the waveforms. Limitations related to these analysis techniques include the subjective nature by which the parameters to be tested are chosen; waveform temporal information is often ignored, there is limited information on the variability of the entire waveform, and the chosen parameters can be highly correlated.[14] Recently, the multivariate analysis technique of principal component analysis (PCA) has been effectively used to analyze gait[15,30,35] and EMG[25,27] waveform data, and this technique has distinctive advantages over the more traditional analysis techniques. Principal component analysis has been shown to have increased sensitivity over traditional parameter-based analysis techniques in detecting differences in kinematic and kinetic data.[53] It is also very capable of (1) reducing the data set's dimensionality, (2) objectively extracting important features from the waveform data based on the variability in the data, and (3) detecting group differences across entire waveforms.[12] Principal component analysis is an orthogonal or eigenvalue decomposition of an original data set into new uncorrelated variables or principal components (PCs). These individual PCs describe salient features of variation within the original data set that can then be related to biomechanical or neuromuscular waveform characteristics. Individual waveforms in the analysis are scored based on their similarity to the extracted features (PCs), and then statistical hypothesis testing can be performed on these scores to test for differences (ie, group, condition).

The purpose of this study was to measure and compare muscle strength, hip, knee, and ankle kinematic and kinetic waveforms, as well as muscle activation waveforms of the quadriceps, hamstrings, and gastrocnemii, during the stance phase of an unanticipated side-cut maneuver in an elite adolescent soccer population using PCA. It was hypothesized that gender and mediolateral muscle site differences would exist in both the magnitude and temporal characteristics of these waveforms and that these differences would help explain risk factors related to the higher prevalence of noncontact ACL injuries in female athletes compared with male athletes. The long-term goal of this study is to use the identified gender and mediolateral muscle site differences collectively to help develop or improve preventive training programs aimed at reducing the incidence of ACL injuries, particularly in female athletes.

METHODS

Subjects

Forty-two healthy elite adolescent soccer players (21 male and 21 female) between the ages of 14 and 18 years (Table 1) were recruited from the Nova Scotia provincial youth and Canada Games soccer teams. Each subject had no significant injury at the time of testing and had no history of major injury to either lower limb (ie, meniscus damage or substantial ligament damage to the knee or ankle). Subjects with previous ankle sprains were permitted to take part in the study if the sprain occurred at least 1 year before testing and they were no longer experiencing any pain while playing soccer. The Research Ethics Board for Health and Medical Sciences at Dalhousie University approved this study, and all subjects, along with their guardians, were required to sign a written consent form before testing.

TABLE 1
Descriptive and Strength Data for Male and Female Subjects[a]

	Male	Female	*P* Value
Anthropometrics			
Age, y	17.0 (0.6)	16.7 (1.0)	.19
Height, m	1.77 (0.05)	1.65 (0.07)	**<.0001**
Weight, kg	69.6 (6.6)	60.8 (5.5)	**<.0001**
BMI, kg/m^2	22.1 (1.7)	22.4 (1.8)	.63
Cutting characteristics			
Approach speed, m/s	3.50 (0.09)	3.44 (0.10)	.08
Soccer experience			
Years played	10.7 (1.7)	9.8 (2.1)	.15
Strength			
KE 45° supine, N·m	139.5 (24.8)	115.5 (20.7)	**.001**
KF 55° prone, N·m	86.8 (22.5)	66.3 (13.8)	**.001**
KF 55° supine, N·m	74.4 (27.5)	52.9 (14.1)	**.003**
PF seated, N·m	122.4 (39.4)	91.0 (21.7)	**.003**
KF 55° supine/KE 45°	0.53 (0.16)	0.46 (0.08)	.10
KF 55° prone/KE 45°	0.62 (0.12)	0.58 (0.11)	.24

[a]BMI, body mass index; KE, knee extension; KF, knee flexion; PF, plantar flexion. Student *t* tests used to test for differences between genders. Statistically significant differences in bold ($P < .05$). Values in parentheses are standard deviations.

Experimental Design

On arrival in the laboratory, subjects viewed a demonstration of the athletic maneuvers and then practiced each maneuver before testing. The three maneuvers included a straight run, a running side-cut between 35° and 60° from the direction of travel (cutting to the left with the right foot planted on the force platform), and a running crosscut between 35° and 60° from the direction of travel (cutting across the body to the right with the right foot planted on the force platform). Two infrared timing gaits were used to ensure that the approach speed was 3.5 ± 0.2 m/s, and just before the subject landed on the force platform, a 3-light guiding system was used to randomly cue the subjects to either run straight, cut to the left (side-cut), or cut to the right (crosscut). Subjects had approximately half a second to react and make the cut, and the maneuvers were repeated until 5 acceptable trials were obtained for the 3 maneuvers. Only the results for the side-cut maneuver are discussed in this article; the results for the straight run and cross-cut maneuvers will be presented in another article (S. C. L. et al, unpublished data, 2007).

EMG and Motion Analysis

A complete 3-dimensional analysis including motion and force data as well as muscle activation patterns of the right leg was conducted for the stance phase of the side-cut. Patient setup began with standard skin preparation (shaving and cleaning with alcohol) followed by placement of silver/silver chloride pellet surface electrodes (0.79 mm^2 contact area, Bortec Inc, Calgary, AB, Canada) over the appropriate muscle locations. The electrodes were attached in a bipolar configuration (20 mm center-to-center) along the direction of the muscle fibers on the right leg for the rectus femoris (RF), VL, VM, LH, MH, lateral gastrocnemius (LG), and medial gastrocnemius (MG).[25,26,31] A reference electrode was positioned over the tibial shaft, and proper electrode placement was validated by assessing the EMG recordings[51] while the subjects performed a series of isolated movements.[29] Raw EMG signals were preamplified (500 times) and further amplified (bandpass 10-1000 Hz, common mode rejection ratio = 115 dB [at 60 Hz], input impedance ~10 Gohm) with an 8-channel surface EMG system (AMT-8 EMG, Bortec Inc).

Motion data were captured at 100 Hz using an Optotrak motion analysis system (Northern Digital Inc, Waterloo, ON, Canada), and ground-reaction force data were captured at 1000 Hz using an AMTI force platform (Advanced Medical Technology Inc, Watertown, Mass). Infrared light-emitting marker diodes were placed on the shoulder, greater trochanter, lateral epicondyle, and lateral malleolus of the right leg. Marker triads consisting of 3 rigidly fixed infrared markers were placed on the pelvis, thigh, shank, and foot. Virtual points including the right and left anterior superior iliac spines, medial epicondyle, fibular head, tibial tuberosity, medial malleolus, second metatarsal head, and calcaneous[10] were collected to create anatomical coordinate systems, and a standing calibration trial was captured as the reference position on which to base all joint angle calculations. To prevent damage and entanglement of the EMG electrode and infrared marker wires during testing, an ultrathin stretchable stocking was placed over the right leg.

On completion of the motion trials, an EMG subject bias trial was recorded with the subject relaxed and supine. Six maximum voluntary isometric contraction (MVIC) exercises were performed to elicit maximal activation amplitudes for the purpose of EMG amplitude normalization.[25] Five of the 6 exercises were performed on a Cybex dynamometer (Lumex Inc, Ronkonkoma, NY), and 4 of these exercises provided a measure of muscle strength (N·m) for the muscle groups. The 6 MVIC exercises included (1) sitting supine and extending the knee at 45°, (2) simultaneously extending the knee at 45° and flexing the hip while sitting supine, (3) flexing the knee at 45° while sitting supine, (4) flexing the knee at 55° while lying prone, (5) plantar flexing the ankle with the knee fully extended and the ankle in a neutral position, and (6) plantar flexing the ankle against a resistance while standing on toes. All torques were gravity corrected, and the EMG data were captured at 1000 Hz.

Data Analysis

Three-dimensional joint angles and net external moments for the hip, knee, and ankle were calculated using Matlab (The MathWorks Inc, Natick, Mass) custom-written inverse dynamics analysis software. The foot, shank, thigh, and pelvis were modeled as rigid bodies, and the position and orientation of these segments were determined using a least squares optimization routine.[11] Joint angles were reported according to the floating axis joint coordinate system[21] with flexion (or plantar flexion at the ankle), internal rotation (or eversion at the ankle), and adduction (or toe-in at the ankle) all being positive for the 3 joints. The net external moments were described with respect to the same rotation axes used for the joint angle data.[30,35,36]

The EMG data were bias corrected, converted to microvolts, full-wave rectified, and low-pass filtered at 6 Hz using a zero-lag fourth-order Butterworth filter in Matlab. All kinematic, kinetic, and EMG waveform data were time normalized with the maneuver's stance phase represented by 101 data points ranging from 0% (foot strike) to 100% (foot off). The moment data were amplitude normalized to body mass, and the EMG data were amplitude normalized to maximal EMG amplitudes attained during the MVIC normalization exercises using a 100-ms moving window algorithm for each muscle.[25] Three to 5 side-cut trials were averaged together to create an ensemble average profile for each waveform measure.

The analysis technique of PCA was applied to the ensemble average angle, moment, and EMG waveforms to identify features of variation in the waveforms that were then tested statistically for gender and/or mediolateral muscle site differences. Principal component analysis is a multidimensional analysis tool that has become increasingly popular for analyzing biomechanical and neuromuscular waveform data in recent years.[12] A data set that includes all the waveforms of a particular variable or measure is first arranged in a matrix, and the mean value at each instant of time is then subtracted from all waveforms in the data set. The covariance matrix of this mean removed data set is calculated and entered into a PC analysis. Principal component analysis involves performing an orthogonal or eigenvector decomposition of the covariance matrix for a group of waveforms to identify or capture biomechanical waveform features (ie, overall magnitudes, local magnitudes, phase shifts, and amplitudes) based on the patterns of variability in the waveform data set. The biomechanical features are represented by the eigenvectors or PCs of the analysis, and then each subject's waveform receives a score (PC score) based on how similar his or her waveform is to that specific PC. Statistical comparisons are performed on the PC scores, and the PCs are ordered in a manner so that the first PC describes the greatest amount of waveform variation, the second PC describes the second greatest amount of variation, and so forth. The salient features that the PCs capture can be discriminatory or nondiscriminatory in nature, and the PC scores that each waveform obtains provide some indication of how much that particular feature is contributing to the overall waveform pattern.

The waveforms for hip, knee, and ankle angles and moments and RF activation patterns for the male and female athletes were analyzed using separate PC analyses for each individual variable or biomechanical or neuromuscular component. Each separate PC analysis involved inputting the male and female waveforms for the particular variable being analyzed into the analysis and then statistically testing the PC scores for gender differences using Student *t* tests. For each of the quadriceps (VL and VM), hamstrings (LH and MH), and gastrocnemii (LG and MG) muscle groups, gender and mediolateral site differences were

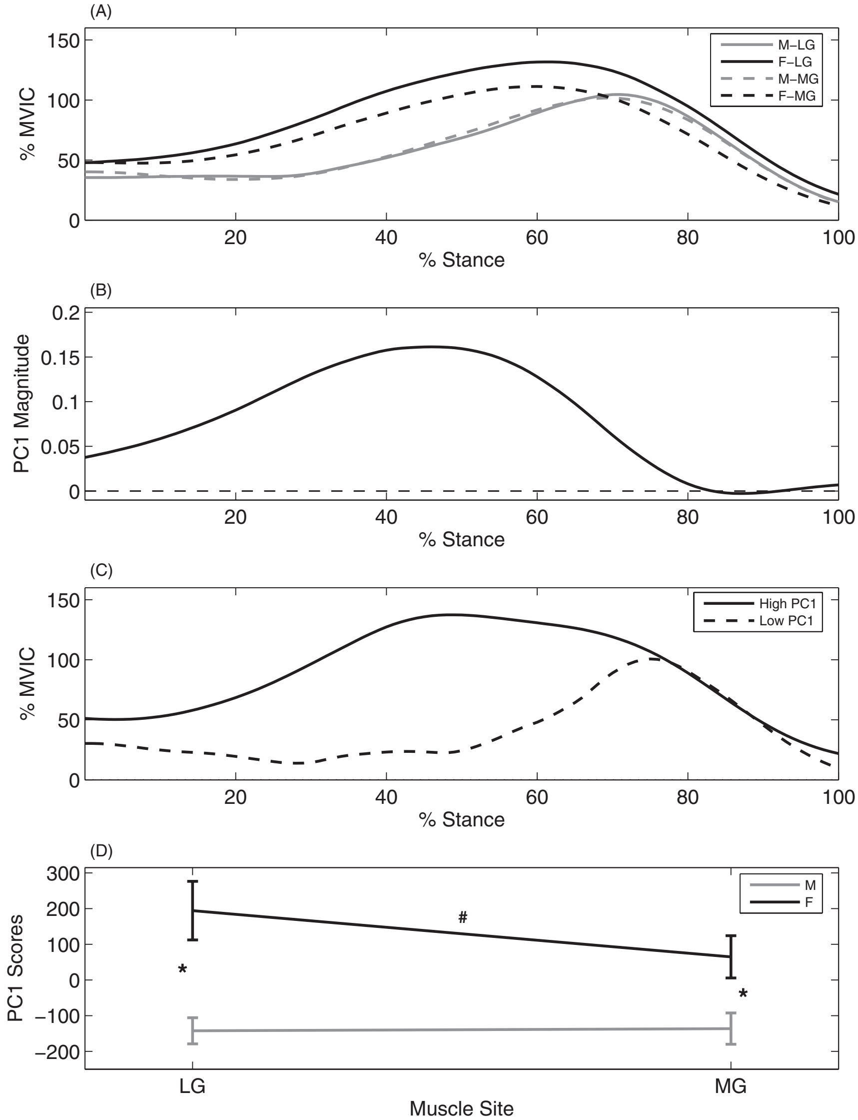

Figure 1. Male (M) and female (F) mean gastrocnemii activation waveforms for the stance phase of the side-cut, principal component (PC) waveform, high and low PC score waveforms, and PC score means. A, group means for the maximum voluntary isometric contraction (MVIC) normalized ensemble average activation waveforms of the lateral gastrocnemius (LG) and medial gastrocnemius (MG) for male and female subjects during the stance phase of the side-cut. B, PC1 capturing the overall muscle activation magnitude during early stance to midstance. C, muscle activation waveforms for 2 subjects with a high and low PC1 score. D, PC1 score means with standard error of the means for the LG and MG of male and female subjects. *Significant gender difference; #significant mediolateral muscle site difference ($P < .05$).

analyzed by simultaneously including medial and lateral muscle site waveforms for both male and female subjects in a separate PC analysis for each of the 3 different muscle groups. A 2-factor mixed-model analysis of variance, with the repeated measure being lateral and medial muscle sites, was used along with Tukey adjusted post hoc pairwise comparisons ($P < .05$) to identify differences between mediolateral muscle sites and between genders for the 3 muscle groups. Gender differences in anthropometric measures, strength, and years of playing experience were tested using Student t tests ($P < .05$). All analyses and statistical testing were performed in Matlab and Minitab (Minitab Inc, State College, Pa).

RESULTS

Subject Demographics and Maneuver Approach Speeds

All subjects were free of injury at the time of testing, although many subjects reported minor lower limb injuries (ie, ankle sprain, muscle strain, and broken bone) previously in their soccer careers (62% of male subjects and 86% of female subjects). The male soccer players were 8.81 kg heavier ($P < .01$) and 0.12 m taller ($P < .01$) than their female counterparts; however, no differences were detected for age, body mass index, and years of playing experience (Table 1).

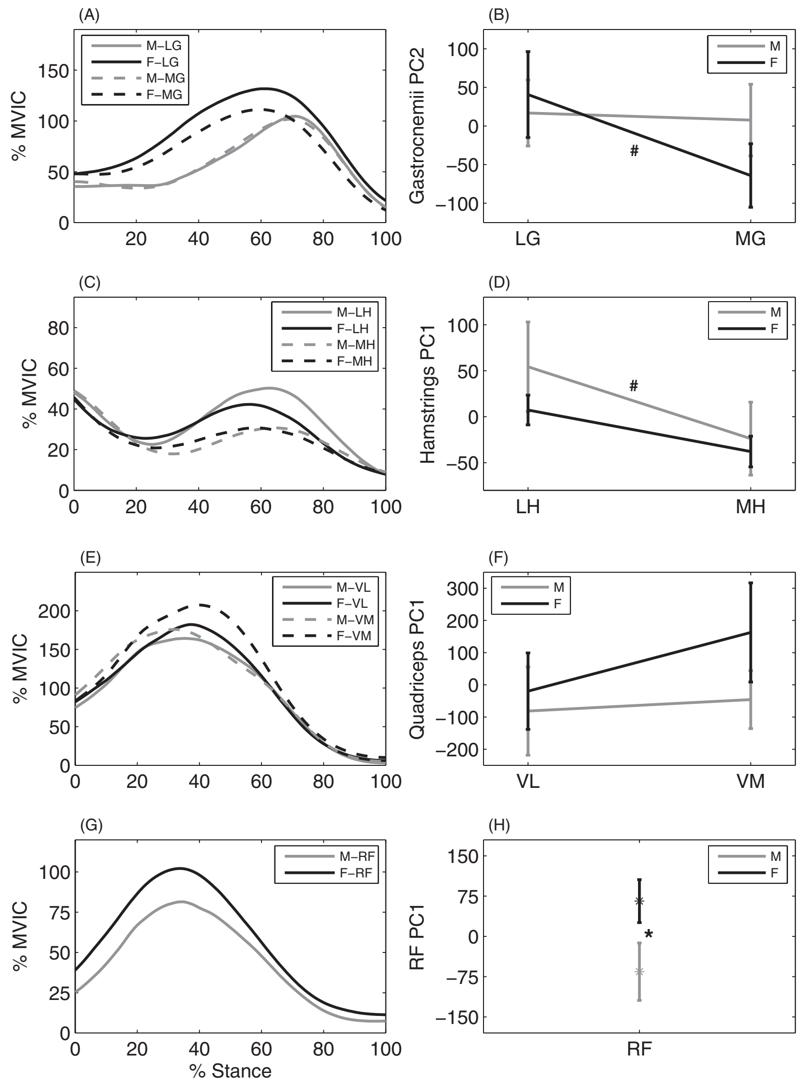

Figure 2. Male (M) and female (F) mean muscle activation waveforms for the stance phase of the side-cut and corresponding principal component (PC) score means. Left column includes group means of the (A) lateral gastrocnemius (LG) and medial gastrocnemius (MG), (C) lateral hamstring (LH) and medial hamstring (MH), (E) vastus medialis (VM) and vastus lateral (VL), and (G) rectus femoris (RF) for the male and female maximum voluntary isometric contraction (MVIC) normalized ensemble average activation waveforms during stance. Right column includes male and female PC score group means with standard error of the means for (B) PC2 (magnitude during late stance) of the LG and MG, (D) PC1 (magnitude throughout stance) for the LH and MH, (F) PC1 (magnitude throughout stance) for the VL and VM, and (H) PC1 (magnitude throughout stance) for the RF. *Significant gender difference; #significant mediolateral muscle site difference (*P* < .05).

The side-cut was performed in an indoor/turf soccer shoe by all athletes, and the approach speed for the maneuver did not differ statistically between the male (3.50 ± 0.09 m/s) and female (3.44 ± 0.10 m/s) groups (Table 1).

Strength Measures

Male players produced greater maximal moments than did female players for knee flexion (prone and supine), knee extension, and ankle plantarflexion strength exercises on the Cybex dynamometer (Table 1). The largest muscle moment mean difference between genders was for plantar flexion while sitting supine, with male subjects generating a 31.4 N·m (*P* < .005) larger moment than female subjects. No statistically significant differences between genders were identified for the ratios of knee flexion (prone and supine) versus knee extension (Table 1). When maximal moments were normalized to the body weight and height of the subjects, no differences between genders for the 4 strength measures were found.

EMG

Four separate PC analyses were performed on the gastrocnemii (LG and MG), hamstrings (LH and MH), quadriceps (VL and VM), and RF muscle activation waveforms to

TABLE 2
Interpretation and *P* Values for the Muscle Activation Principal Component (PC) Waveforms During the Side-Cut Maneuver[a]

Muscle Group	PC	Interpretation	Gender Comparison, *P* Value	Med-Lat Site Comparison, *P* Value
Gastrocnemii (LG & MG)	PC1	Magnitude during early stance to midstance (≈0% to 70%)	Med site, **<.003** Lat site, **<.003**	Male, 1.0 Female, **.05**
	PC2	Magnitude during late stance (≈70% to 100%)	Med site, .14 Lat site, .89	Male, 1.0 Female, **.02**
Hamstrings (LH & MH)	PC1	Magnitude throughout stance	Med site, .95 Lat site, .29	Male, **.02** Female, .32
	PC2	Magnitude/shape during early stance and midstance	Med site, .62 Lat site, .97	Male, **.001** Female, .09
Quadriceps (RF site only)	PC1	Magnitude throughout stance	__, .05	__ , __

[a]Med, medial; lat, lateral; LG, lateral gastrocnemius; MG, medial gastrocnemius; LH, lateral hamstring; MH, medial hamstring; RF, rectus femoris. Dashes mean that comparisons were not made. Repeated-measures analysis of variance used on PC scores for hamstrings and gastrocnemii activation waveforms, using Tukey adjusted post hoc pairwise comparisons. Student *t* tests used to test for differences in PC scores for RF. Significant differences in bold ($P < .05$).

compare the male and female ensemble average muscle activation waveforms for the side-cut maneuver. The first 3 PCs for the 4 analyses explained the majority of the total variance in the magnitude and overall shape pattern of the temporal waveforms. The total variance explained by these 3 PCs was 96.5%, 93.3%, 97.2%, and 97.1% for the gastrocnemii, hamstrings, quadriceps, and RF activation waveforms, respectively. The general overall magnitude of the activation waveforms during stance was captured by PC1 for the hamstrings, quadriceps, and RF. For the gastrocnemii, PC1 captured early stance to midstance activation magnitudes (≈0% to 70% of stance), and PC2 captured late stance (≈70% to 100% of stance) activation magnitudes. The remaining PCs captured more subtle features of the temporal waveforms, and these features were not as effective in detecting gender or muscle site differences. Two female VM activation waveforms and 3 male MG activation waveforms were not included in the analyses because of insufficient signal quality during the MVIC normalization trials.

Gastrocnemii Activation Waveforms

Figure 1 provides an example of the gastrocnemii ensemble average waveforms (Figure 1A) along with the PC1 loading vector that captured an overall magnitude during early stance to midstance (Figure 1B). The waveforms from an individual with a high and low PC1 score (Figure 1C) for each analysis were used to help with interpretation of the waveform features. Means of the PC scores corresponding to the waveform magnitudes and standard errors of these means for each group were also plotted (Figure 1D).

Gender and mediolateral muscle site differences in activation magnitudes during the side-cut were captured for the gastrocnemii (Table 2). Pairwise comparisons of the PC1 scores illustrated that the female LG and MG had larger overall magnitudes than the male LG and MG ($P < .003$) during early stance to midstance. For the same phase of stance and comparing the medial and lateral muscle sites within gender, females had higher LG activation magnitudes compared with their MG ($P = .05$), whereas statistically significant differences were not identified between the male MG and LG muscle sites. During late stance, a mediolateral muscle activation imbalance was detected in female subjects only, with the LG being more activated than the MG ($P = .02$) (Figures 2 A and B).

Hamstrings Activation Waveforms

No overall activation magnitude differences between genders were detected by PC1 throughout the entirety of stance for both the LH and MH (Table 2). In male subjects, however, LH activity was greater than MH activity throughout stance ($P = .02$), but this mediolateral imbalance was not present in female subjects (Figures 2 C and D). The relationship between muscle activation levels during early stance and midstance was captured by PC2 (see Figure A1 in Appendix A, available in the online version of this article at http://ajsm.sagepub.com/cgi/content/full/35/11/1888/DC1/ for PC waveform) with the difference being statistically significant in male subjects only (male $P = .001$; female $P = .09$). For this feature, the LH and MH mean activation levels were comparable during early stance; however, the main difference was during midstance where the LH activity was significantly higher with a more distinctive peak than the MH in male subjects only. The MH demonstrated on average greater activity during early stance compared with midstance. A female difference may not have been detected for the PC2 feature because of a lack of adequate power (0.645).

Quadriceps Activation Waveforms

The PC analysis of the quadriceps that simultaneously tested the VL and VM for both genders found no gender or

TABLE 3
Interpretation, Gender Means, Standard Error of the Means, and *P* Values for the Kinematic and Kinetic Principal Component (PC) Waveforms During the Side-Cut Maneuver[a]

				PC Score Means (SEM)		
	Gait Measure	PC	Interpretation	Male	Female	*P* Value
Joint angles						
	Hip flex/ext	PC1	Magnitude throughout stance	36.2 (21.3)	–36.2 (17.0)	**.01**
	Hip int/ext rotation	PC1	Magnitude throughout stance	27.6 (18.4)	–27.6 (15.3)	**.03**
		PC2	Amplitude/shape throughout stance	11.1 (7.3)	–11.1 (8.0)	**.05**
	Knee flex/ext	PC1	Magnitude throughout stance	9.0 (18.9)	–9.0 (13.9)	.45
	Ankle plantar flexion/dorsiflexion	PC3	Phase shift throughout stance	–8.6 (4.8)	8.6 (4.8)	**.02**
Joint moments						
	Hip flex/ext	PC2	Magnitude throughout stance	1.38 (0.64)	–1.38 (0.52)	**.02**
		PC3	Amplitude during early stance (≈0% to 20%)	–0.67 (0.54)	0.67 (0.45)	.06
	Hip int/ext rotation	PC3	Magnitude during early stance (≈0% to 12%)	–0.16 (0.09)	0.16 (0.10)	**.03**
	Hip adduct/abduct	PC3	Magnitude during early stance (≈0% to 12%)	0.42 (0.21)	–0.42 (0.33)	**.04**
	Knee adduct/abduct	PC3	Magnitude during early stance (≈0% to 12%)	0.23 (0.16)	–0.23 (0.18)	.06
	Ankle evert/invert	PC4	Magnitude during early stance (≈0% to 20%)	–0.045 (0.04)	0.045 (0.02)	**.05**

[a]SEM, standard error of measurement; flex, flexion; ext, extension; int, internal; ext, external; adduct, adduction; abduct, abduction; evert, eversion; invert, inversion. Student *t* tests used to test for differences between genders in the PC scores for kinematic and kinetic waveforms. Statistically significant differences in bold ($P < .05$).

mediolateral muscle site differences (Figures 2E and F). Analyzing the RF muscle site, however, demonstrated larger activation magnitudes in female subjects compared with male subjects throughout stance ($P = .05$) (Table 2 and Figures 2G and H).

Kinematics

Principal component analysis was used to test for differences in joint angle waveforms for the hip, knee, and ankle between male and female players. Knee adduction and internal rotation angles were not examined because their relative values are of a comparable magnitude to measurement errors from marker skin motion and kinematic cross talk.[4,28,42] Joint angle differences between genders were most prominent at the hip, with more subtle differences evident at the ankle and no significant differences present at the knee. The first 3 PCs for each joint angle component at all joints captured between 94.6% and 99.0% of the total variance in the waveform data. To aid with interpreting the results from the PC analysis, all kinematic and kinetic PC waveforms that were statistically significant or approached significance (Table 3) are plotted in Figure A1 in Appendix A, along with the percent variation explained by each specific PC.

Principal component 1 for hip flexion and hip internal rotation described the overall magnitude throughout stance (Table 3). Female subjects demonstrated significantly less hip flexion than male subjects (Figure 3A). Mean hip flexion at foot strike was 38.9° ± 8.8° and 44.1° ± 7.6° for female and male subjects, respectively, and this approximate magnitude difference was evident throughout stance. Internal rotation angles throughout stance were also different, with male subjects having a more internally rotated femur than female subjects, who had a more externally rotated femur ($P = .03$) (Figure 3B). Male subjects had a mean internal rotation angle during stance of 3.00° ± 1.78°, whereas female subjects had a mean external rotation angle of 2.48° ± 2.3°. Principal component 2 captured a difference in the pattern of the internal rotation angle with male subjects maintaining a more steady-state internal rotation angle throughout stance compared with female subjects, who tended to go from internal to external rotation as stance phase progressed ($P = .05$). Gender differences in hip adduction were not detected.

Knee flexion angle differences between genders were not found (Figure 3C), and the only gender difference captured in ankle kinematics was a subtle shift in the timing of the plantarflexion waveforms (Figure 3D). Female subjects tended to dorsiflex their ankles sooner during early stance to midstance and plantar flex the ankle sooner during late stance in comparison with the male athletes (PC3 $P = .02$) (Table 3).

Kinetics

Differences in joint moments between genders were identified for all 3 joints, both throughout the entire stance phase and at specific instants of stance (Table 3 and Figure 4).

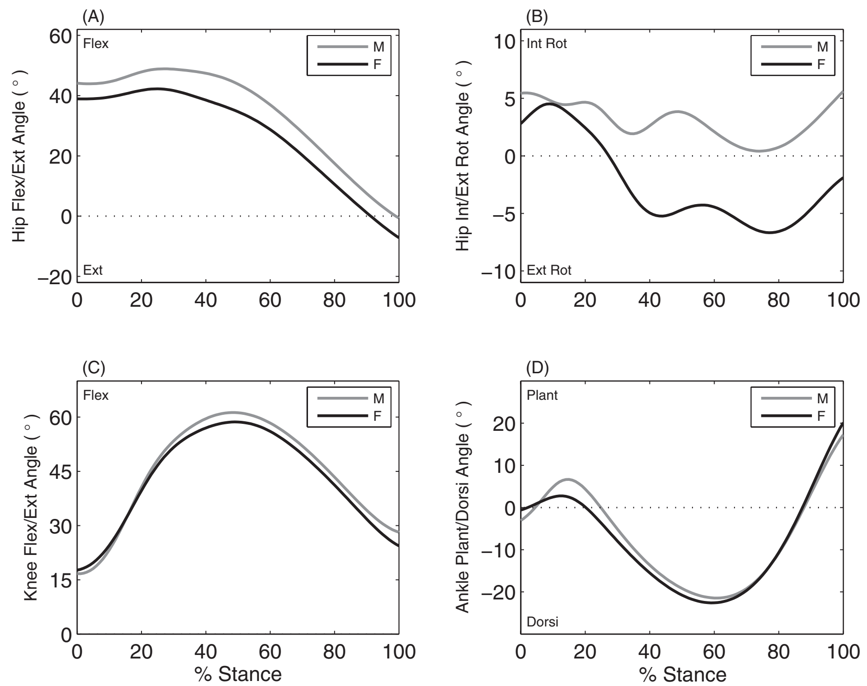

Figure 3. Male (M) and female (F) mean joint angle waveforms for the stance phase of the side-cut. A, hip flexion and extension; B, hip internal and external rotation; C, knee flexion and extension; D, ankle plantar flexion and dorsiflexion.

Four PCs were examined for each joint moment, and generally the third and fourth PCs captured waveform differences during early stance. The first 4 PCs for the 3 ankle moments captured at least 96.6% of the total waveform variance. For the knee and hip, at least 81.2% and 86.1% of the moment waveform variance was captured by the first 4 PCs, respectively.

The most notable moment differences captured between genders occurred at the hip followed by less subtle differences at the ankle and knee. Principal component 2 for hip flexion moment captured the overall magnitude throughout stance, with male athletes exhibiting a greater flexion moment magnitude compared with female athletes for the duration of stance ($P = .002$) (Figure 4A). Principal component 3 also captured a feature of variation in hip flexion moment magnitude during the early stance (≈ first 10%); however, this feature was not quite statistically significant for a gender difference ($P = .06$).

Differences between male and female athletes in hip internal rotation (Figure 4B) and hip adduction moment magnitudes (Figure 4C) were captured during the first approximate 12% of stance by PC3. Female subjects generated a larger hip external rotation moment than male subjects ($P = .03$) and tended to have a hip adduction moment during the early stance phase in comparison with male subjects, who had a hip abduction moment during the early stance phase ($P = .04$) (Table 3).

No differences between genders for knee flexion moment were found (Figure 4D), and the only moment difference that approached significance at the knee was adduction moment during the first 12% of stance ($P = .06$) (Figure 4E). Principal component 3 captured this magnitude difference, with male subjects having a larger abduction moment than female subjects during early stance. With respect to the ankle, PC4 captured a gender difference in eversion moment during the first 20% of stance ($P = .05$) (Figure 4F). Male athletes were more apt to experience a small eversion moment during the first 20% of stance followed by the generation of a larger inversion moment for the remainder of stance. Female athletes, however, produced an inversion moment immediately after foot strike and maintained this inversion moment throughout stance.

Results Summary

Differences were found in kinematic, kinetic, and muscle activation waveforms between genders as well as between medial and lateral sites for the side-cut maneuver. Features of variation related to the overall magnitude and pattern of the waveforms were captured with the most notable gender differences being detected for the gastrocnemii and RF activation patterns and hip flexion angle and moment waveforms. Female subjects had higher activated LG, MG, and RF and also demonstrated a reduced hip flexion angle and moment compared with male subjects throughout the stance phase. Principal component 3 and PC4 for several joint moment measures (hip adduction, hip internal rotation, knee adduction, and ankle eversion) also captured gender-related differences, particularly within the first 20% of stance.

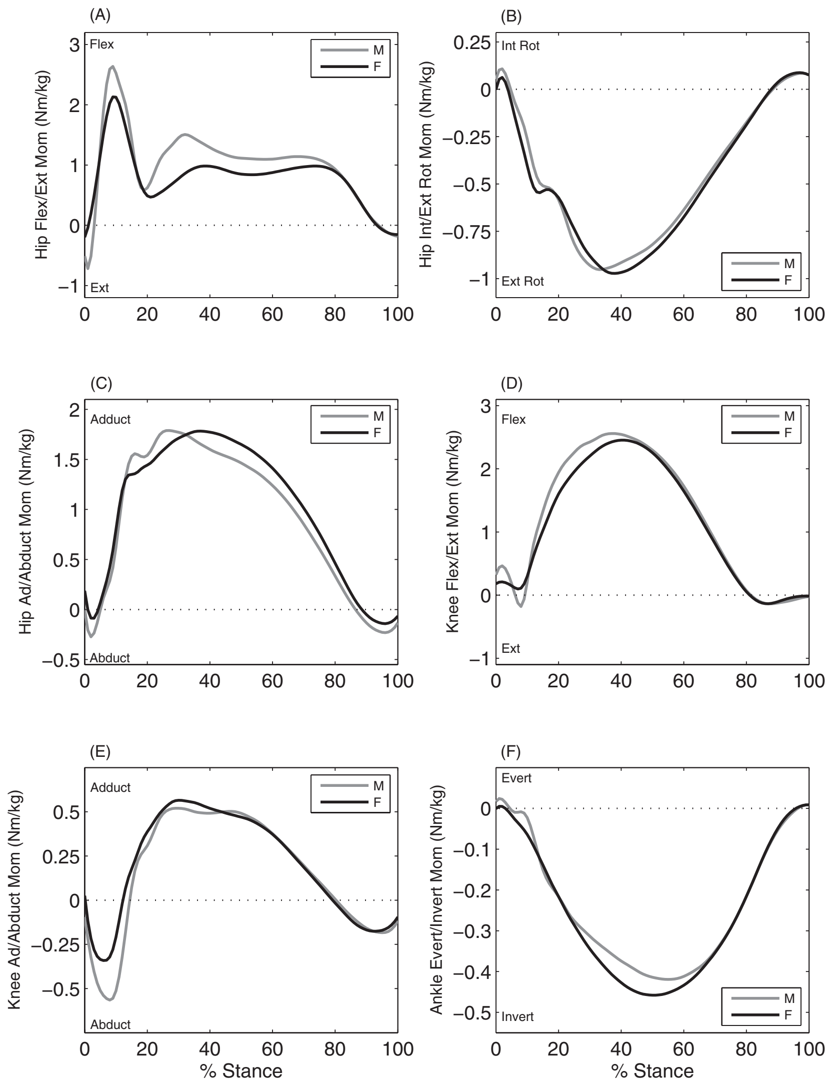

Figure 4. Male (M) and female (F) mean joint moment waveforms for the stance phase of the side-cut. A, hip flexion and extension; B, hip internal and external rotation; C, hip adduction and abduction; D, knee flexion and extension; E, knee adduction and abduction; F, ankle eversion and inversion.

DISCUSSION

This study identified neuromuscular and biomechanical differences between genders in an elite adolescent soccer population during an unanticipated side-cut maneuver. The application of PCA to the muscle activation waveforms demonstrated that female athletes have greater LG, MG, and RF muscle activation magnitudes during the stance phase of the side-cut than male athletes. Female athletes also exhibited smaller hip flexion angle and moment magnitudes throughout stance compared with male athletes. Hip adduction, hip internal rotation, knee adduction, and ankle eversion moment differences were also captured by PCA during the first approximate 10% to 20% of stance, when noncontact ACL injuries most often occur.[8] With respect to strength measures for knee flexion, knee extension, and ankle plantar flexion, no differences were identified between genders for the generated moments normalized to body weight and height. The ratio of knee flexion strength to knee extension strength was also compared between male and female athletes, and no differences were detected.

Muscle activation magnitude differences between the gastrocnemii of male and female athletes during the side-cut were the most notable differences identified in our study, and the contribution of these differences as potential risk factors for ACL injury has not been previously addressed in the literature. No previous study on cutting maneuvers has compared gastrocnemii activity between genders, and landing studies analyzing the gastrocnemii have not identified gender-related differences.[13,16,45] In our study, female subjects demonstrated greater LG and MG activity than male subjects during early stance to midstance. In female subjects only, a mediolateral muscle site imbalance for the entire stance duration of the side-cut was also evident, with the LG being more active than the MG. Male subjects exhibited similar activation magnitudes for the medial and lateral sites throughout stance.

The higher gastrocnemii activity may be necessary to help the quadriceps and hamstrings stabilize and stiffen the female knee joint, which tends to be more lax and less stiff than the male knee joint.[24,52] Although the higher gastrocnemii activity in female athletes could help protect the knee, it may also increase ACL strain. Studies using a computer-based model[41] and a differential variable transducer implanted on the ACL[17] have shown that contraction of the gastrocnemii alone or in combination with the quadriceps is able to increase the load on the ACL. As well, the mediolateral site imbalance present in only female subjects may also be a risk factor, and further investigation is warranted to determine if this imbalance places the knee or the posterolateral aspect of the knee in a more vulnerable state for injury.

In addition to greater LG and MG activity, female athletes demonstrated greater RF activity throughout stance compared with male athletes. Contraction of the quadriceps at knee flexion angles less than approximately 45° can increase ACL strain,[3,44] and therefore the higher RF activity in female athletes may increase ACL strain during the side-cut and potentially place them at greater risk of ACL injury.

Differences in VL and VM activity between male and female subjects were not found, in contrast to the findings of Malinzak et al[32] and Sigward and Powers.[46] Both studies had subjects perform the side-cut in a preplanned manner and at an approach speed greater than 5.0 m/s. Malinzak et al demonstrated greater VL and VM activity in female athletes (averaged together) throughout stance, whereas Sigward and Powers demonstrated greater VL activity in female athletes compared with male athletes during early stance. The unanticipated nature of the side-cut, the slower approach speeds (3.5 ± 0.2 m/s), and the differences in skill levels among these studies, with ours having more skilled athletes, may have contributed to the different findings. Although future investigations are recommended with respect to the influence that the RF has on ACL injuries and the hip, capturing gender differences in RF activity and not in VM and VL activity suggests that female athletes might possibly be activating the biarticulate RF muscle at a greater magnitude than male athletes to help more with controlling of the hip rather than the knee.

Differences between male and female subjects in hamstring activation magnitudes were not captured, and these findings agree with Sigward and Powers,[46] who also found no differences between genders in hamstring activity levels during early stance. Malinzak et al,[32] however, reported that female athletes have smaller hamstring activation magnitudes (LH and MH averaged together) than male athletes during stance of a preplanned straight run, side-cut, and crosscut, with the differences being most pronounced for the straight run and crosscut. Differences in hamstring findings between the studies might possibly be attributed to the subjects being tested. Sigward and Powers and our study used more skilled and experienced teenage soccer players, whereas Malinzak et al[32] used older recreational athletes to make gender comparisons.

Contracting the hamstrings at knee flexion angles greater than approximately 30° can reduce ACL strain by increasing knee joint stability and resisting anterior tibial translation with respect to the femur.[39,44] A reduction in hamstring function during cutting or landing is a potential ACL injury risk factor, and although we were not able to identify hamstring differences between genders, we did identify a statistically significant mediolateral hamstring muscle imbalance present in the male subjects that was not significant in the female subjects. The LH was activated at a greater magnitude than the MH in male subjects, and this difference was particularly evident during midstance when the knee was experiencing large flexion, adduction, and external rotation moments. It is difficult to conclude if this mediolateral site imbalance exists to help male athletes perform the side-cut more efficiently or if it serves as a protective mechanism against the higher rotational moments present during the side-cut. The higher LH activity in male athletes could also provide increased stability to the posterolateral corner, where structural damage and bone bruising often occur in tandem with noncontact ACL injuries.[9,48]

Sagittal plane kinematic differences between male and female athletes were captured at the hip but not at the knee for the unanticipated side-cut maneuver. Similar to the findings of McLean et al,[37] hip flexion angles throughout stance of the side-cut were smaller in female subjects than in male subjects. With respect to the knee, no differences between gender were identified, and this agrees with previous side-cut studies.[18,43,46] It must be noted that flexion angle differences between genders do vary throughout the literature, with other studies reporting different results. In contrast to our findings, Pollard et al[43] found no hip flexion differences between genders, and with respect to the knee, Malinzak et al[32] and McLean et al[37] determined that female athletes performed the side-cut with less knee flexion than male athletes. Although flexion angle results vary across cutting studies, cutting with less hip or knee flexion can place an individual in a more erect posture. Small flexion angles have been shown to generate higher impact forces,[19,49] and therefore the reduced hip flexion angles in female athletes might possibly increase knee joint loadings and thereby place the ACL at greater risk of injury. The gender differences in hip internal rotation and ankle plantar flexion were relatively small and were both deemed to be clinically irrelevant with respect to risk factors for ACL injury. In contrast to our findings where gender differences were not detected for ankle eversion-inversion, Ford et al[18] found that female athletes side-cut with a greater maximum eversion angle and a decreased maximum inversion angle than male athletes. The discrepancies between these 2 studies can most likely be attributed to the method in which the unanticipated side-cuts were performed. Our subjects ran straight before making the side-cut, whereas the subjects studied by Ford et al performed a forward jump, and then a light randomly cued the subjects to side-cut to either the left or right side.

Gender differences were captured for hip flexion moment, with male athletes having a larger overall flexion moment magnitude than female athletes throughout stance. Although requiring further investigation, this greater hip flexion moment combined with a greater hip flexion angle in male athletes could help to increase hip joint stability and thereby make the ACL less vulnerable to injury compared with their female counterparts. Other kinetic differences between genders were also detected during the first 10% to 20% of stance, where ACL injuries are most likely to occur. These differences were captured for hip internal rotation, hip adduction, and ankle eversion moment; however, the moment magnitudes were much smaller than the maximal moments reached later in midstance. It remains unclear if these moment differences at the smaller magnitudes during early stance serve as potential risk factors for ACL injury.

Limitations related to the analysis technique and the testing protocol were acknowledged in this study. The waveform analysis technique of PCA was effective in identifying features in the biomechanical and neuromuscular waveform data that were statistically different between the male and female athletes. The limitation of this analysis technique, however, was that once differences were detected, the magnitudes of these differences were not quantifiable with respect to the units in which the waveforms were reported. The second limitation, related to the testing protocol, was that the athletes were told to side-cut in a manner that felt natural to them, and this most likely introduced variability in the data based on individual differences in cutting technique, making it more difficult to detect differences.

CONCLUSION

This comprehensive study represents the first time PCA has been used successfully to detect biomechanical and neuromuscular differences between genders during an unanticipated running side-cut maneuver in an elite adolescent soccer population. Using the variation in the waveform data, PCA objectively identified a number of biomechanical and neuromuscular features that potentially serve as risk factors in the predisposition of higher ACL injury rates in female athletes compared with male athletes. This was the first study to demonstrate that female athletes have greater gastrocnemii activity and a mediolateral gastrocnemii muscle site magnitude imbalance that is not present in male athletes during side-cutting. Other differences identified that may have a contributing role toward higher ACL injury rates in female athletes include greater RF activity in female athletes and reduced hip flexion angles and moments throughout the stance portion of the unanticipated side-cut.

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REFERENCES

1. 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;33:524-530.
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;23:694-701.
3. 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;12:8-18.
4. Benoit DL, Ramsey DK, Lamontagne M, Xu L, Wretenberg P, Renstrom P. Effect of skin movement artifact on knee kinematics during gait and cutting motions measured in vivo. *Gait Posture*. 2006; 24:152-164.
5. Besier TF, Lloyd DG, Ackland TR. Muscle activation strategies at the knee during running and cutting maneuvers. *Med Sci Sports Exerc*. 2003;35:119-127.
6. Besier TF, Lloyd DG, Ackland TR, Cochrane JL. Anticipatory effects on knee joint loading during running and cutting maneuvers. *Med Sci Sports Exerc*. 2001;33:1176-1181.
7. Besier TF, Lloyd DG, Cochrane JL, Ackland TR. External loading of the knee joint during running and cutting maneuvers. *Med Sci Sports Exerc*. 2001;33:1168-1175.
8. Boden BP, Dean GS, Feagin JA Jr, Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23:573-578.
9. Bretlau T, Tuxoe J, Larsen L, Jorgensen U, Thomsen HS, Lausten GS. Bone bruise in the acutely injured knee. *Knee Surg Sports Traumatol Arthrosc*. 2002;10:96-101.
10. Cappozzo A, Catani F, Croce UD, Leardini A. Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clin Biomech (Bristol, Avon)*. 1995;10:171-178.
11. Challis JH. A procedure for determining rigid body transformation parameters. *J Biomech*. 1995;28:733-737.
12. Chau T. A review of analytical techniques for gait data, part 1: fuzzy, statistical and fractal methods. *Gait Posture*. 2001;13:49-66.
13. Cowling EJ, Steele JR. Is lower limb muscle synchrony during landing affected by gender? Implications for variations in ACL injury rates. *J Electromyogr Kinesiol*. 2001;11:263-268.
14. Deluzio KJ, Astephen JL. Biomechanical features of gait waveform data associated with knee osteoarthritis: an application of principal component analysis. *Gait Posture*. 2007;25:86-93.
15. Deluzio KJ, Wyss UP, Zee B, Costigan PA, Sorbie C. Principal component models of knee kinematics and kinetics: normal vs. pathological gait patterns. *Hum Mov Sci*. 1997;16:201-217.
16. Fagenbaum R, Darling WG. Jump landing strategies in male and female college athletes and the implications of such strategies for anterior cruciate ligament injury. *Am J Sports Med*. 2003;31:233-240.
17. Fleming BC, Renstrom PA, Ohlen G, et al. The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *J Orthop Res*. 2001;19:1178-1184.
18. Ford KR, Myer GD, Toms HE, Hewett TE. Gender differences in the kinematics of unanticipated cutting in young athletes. *Med Sci Sports Exerc*. 2005;37:124-129.
19. Gauffin H, Tropp H. Altered movement and muscular-activation patterns during the one-legged jump in patients with an old anterior cruciate ligament rupture. *Am J Sports Med*. 1992;20:182-192.
20. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg*. 2000;8:141-150.
21. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng*. 1983;105:136-144.
22. Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes, part 1: mechanisms and risk factors. *Am J Sports Med*. 2006;34:299-311.
23. Houck JR, Duncan A, De Haven KE. Comparison of frontal plane trunk kinematics and hip and knee moments during anticipated and unanticipated walking and side step cutting tasks. *Gait Posture*. 2006;24:314-322.

24. Hsu WH, Fisk JA, Yamamoto Y, Debski RE, Woo SL. Differences in torsional joint stiffness of the knee between genders: a human cadaveric study. *Am J Sports Med*. 2006;34:765-770.
25. Hubley-Kozey CL, Deluzio KJ, Landry SC, McNutt JS, Stanish WD. Neuromuscular alterations during walking in persons with moderate knee osteoarthritis. *J Electromyogr Kinesiol*. 2006;16:365-378.
26. Hubley-Kozey CL, Smits E. Quantifying synergist activation patterns during maximal plantarflexion using an orthogonal expansion approach. *Hum Mov Sci*. 1998;17:347-365.
27. Hubley-Kozey CL, Vezina MJ. Differentiating temporal electromyographic waveforms between those with chronic low back pain and healthy controls. *Clin Biomech (Bristol, Avon)*. 2002;17:621-629.
28. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. *J Orthop Res*. 1990;8:383-392.
29. Kendall FP, McCreary EK, Provance PG. *Muscles Testing and Function*. 4th ed. Baltimore, Md: Williams & Wilkins; 1993.
30. Landry SC, McKean KA, Hubley-Kozey CL, Stanish WD, Deluzio KJ. Knee biomechanics of moderate OA patients measured during gait at a self-selected and fast walking speed. *J Biomech*. 2006 Nov 3; [Epub ahead of print].
31. Leveau B, Andersson GBJ. Output forms: data analysis and applications. In: Soderberg GL, ed. *Selected Topics in Surface Electromyography for Use in the Occupational Setting: Expert Perspectives*. Washington, DC: U.S. Department of Health and Human Services; 1992:69-102.
32. 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;16:438-445.
33. 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;13:930-935.
34. Markolf KL, O'Neill G, Jackson SR, McAllister DR. Effects of applied quadriceps and hamstrings muscle loads on forces in the anterior and posterior cruciate ligaments. *Am J Sports Med*. 2004;32:1144-1149.
35. McKean KA, Landry SC, Hubley-Kozey CL, Dunbar MJ, Stanish WD, Deluzio KJ. Gender differences exist in osteoarthritic gait. *Clin Biomech*. 2007 Jan 17; [Epub ahead of print].
36. McLean SG, Huang X, van den Bogert AJ. Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury. *Clin Biomech (Bristol, Avon)*. 2005;20:863-870.
37. 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;36:1008-1016.
38. McLean SG, Neal RJ, Myers PT, Walters MR. Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. *Med Sci Sports Exerc*. 1999;31:959-968.
39. More RC, Karras BT, Neiman R, Fritschy D, Woo SL, Daniel DM. Hamstrings—an anterior cruciate ligament protagonist: an in vitro study. *Am J Sports Med*. 1993;21:231-237.
40. Noyes FR, Mooar PA, Matthews DS, Butler DL. The symptomatic anterior cruciate-deficient knee, part I: the long-term functional disability in athletically active individuals. *J Bone Joint Surg Am*. 1983;65:154-162.
41. O'Connor JJ. Can muscle co-contraction protect knee ligaments after injury or repair? *J Bone Joint Surg Br*. 1993;75:41-48.
42. Piazza SJ, Cavanagh PR. Measurement of the screw-home motion of the knee is sensitive to errors in axis alignment. *J Biomech*. 2000;33:1029-1034.
43. Pollard CD, Davis IM, Hamill J. Influence of gender on hip and knee mechanics during a randomly cued cutting maneuver. *Clin Biomech (Bristol, Avon)*. 2004;19:1022-1031.
44. 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;14:83-87.
45. Rozzi SL, Lephart SM, Gear WS, Fu FH. Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. *Am J Sports Med*. 1999;27:312-319.
46. 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;21:41-48.
47. Simonsen EB, Magnusson SP, Bencke J, et al. Can the hamstring muscles protect the anterior cruciate ligament during a side-cutting maneuver? *Scand J Med Sci Sports*. 2000;10:78-84.
48. Speer KP, Spritzer CE, Bassett FH III, Feagin JA Jr, Garrett WE Jr. Osseous injury associated with acute tears of the anterior cruciate ligament. *Am J Sports Med*. 1992;20:382-389.
49. Swartz EE, Decoster LC, Russell PJ, Croce RV. Effects of developmental stage and sex on lower extremity kinematics and vertical ground reaction forces during landing. *J Athl Train*. 2005;40:9-14.
50. von Porat A, Roos EM, Roos H. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. *Ann Rheum Dis*. 2004;63:269-273.
51. Winter DA, Fuglevand AJ, Archer SE. Crosstalk in surface electromyography—theoretical and practical estimates. *J Electromyogr Kinesiol*. 1994;4:15-26.
52. 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;85:782-789.
53. Wrigley AT, Albert WJ, Deluzio KJ, Stevenson JM. Differentiating lifting technique between those who develop low back pain and those who do not. *Clin Biomech (Bristol, Avon)*. 2005;20:254-263.