American Journal of Sports Medicine

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Am. J. Sports Med. 2007; 35; 1901 originally published online Aug 29, 2007;
DOI: 10.1177/0363546507307400

Neuromuscular and Lower Limb Biomechanical Differences Exist Between Male and Female Elite Adolescent Soccer Players During an Unanticipated Run and Crosscut Maneuver

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Background: Noncontact anterior cruciate ligament injuries often occur during sports such as soccer and basketball in which cutting or landing maneuvers are frequently performed. These injuries are more common in female athletes, and identifying biomechanical or neuromuscular risk factors related to gender may help with the development of preventive training programs aimed at reducing anterior cruciate ligament injury.

Hypothesis: Lower limb biomechanical and/or neuromuscular differences between male and female soccer players will be identified during unanticipated running and cutting maneuvers.

Study Design: Descriptive laboratory study.

Methods: A complete 3-dimensional kinematic, kinetic, and electromyographic analysis of the lower limb for an unanticipated straight-run and crosscut maneuver was performed on 42 (male, 21; female, 21) elite adolescent soccer players.

Results: For both maneuvers, female players had greater lateral gastrocnemius activity, normalized to maximal voluntary isometric contractions, and demonstrated a mediolateral gastrocnemii imbalance that was not present in male players. Rectus femoris activity for both maneuvers and vastus medialis and lateralis activity for the straight run only were also greater in female than in male athletes. Other notable differences captured for the maneuvers included female players having reduced hamstring activity, a reduced hip flexion moment, a reduced hip flexion angle, and an increased ankle eversion angle throughout stance compared with male players.

Conclusion: This is one of the first studies to identify gastrocnemii differences between genders as a possible anterior cruciate ligament injury risk factor. Additional biomechanical and neuromuscular differences were also identified as potential risk factors.

Clinical Relevance: These findings provide insight into the noncontact anterior cruciate ligament injury gender bias and may help improve preventive training programs.

Keywords: anterior cruciate ligament (ACL) injury; electromyography (EMG); gender; kinematics; kinetics; crosscut; running; unanticipated

The ACL is often injured when athletes execute running and crosscutting maneuvers during sport activities such as soccer, basketball, and rugby. Approximately 70% to 80% of all ACL injuries are noncontact in nature,[7,31] and compared with male athletes, female athletes are 2 to 8 times more likely to sustain an injury to the ACL.[1,22] Numerous risk factors for noncontact ACL injuries have been identified in the

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No potential conflict of interest declared.

The American Journal of Sports Medicine, Vol. 35, No. 11
DOI: 10.1177/0363546507307400

literature,[15,16,41] and focusing on potentially modifiable risk factors related to body positioning, joint loading, and neuromuscular coordination could potentially help with preventing and reducing the incidence of this devastating injury.

The understanding of the gender bias associated with noncontact ACL injuries has been enhanced by comparing lower limb biomechanics and neuromuscular control strategies between genders in the laboratory, while the athletes execute running and cutting maneuvers. Most of these gender comparative studies have focused on the side-cut,[11,21,25-28,34,37] with only a select few focusing on running or crosscutting.[9,21,28]

Ferber et al[9] analyzed hip and knee joint kinematics and kinetics during straight running and found that women generated greater peak hip adduction, peak hip internal rotation, and peak knee abduction angles compared with their male counterparts. Although joint moments were measured in that study, statistical comparisons between genders were not carried out. Malinzak et al[21] analyzed a straight run, crosscut, and side-cut and related neuromuscular and knee kinematic differences between genders to ACL injury risk factors. Female subjects demonstrated larger knee abduction angles and reduced knee flexion angles compared with male subjects for the 3 maneuvers. Noncontact ACL injuries frequently occur with the knee close to full extension and in an abducted position during jumping and cutting tasks performed in sports such as soccer and basketball.[7,33] Therefore, these kinematic gender differences may have a contributing role toward the greater noncontact ACL injury rate seen in female athletes.

Malinzak et al[21] also found that women had greater quadriceps activity and less hamstring activity than men did during the preplanned running and cutting maneuvers. Although it is difficult to conclude that these activation differences are increasing ACL strain during the dynamic activities, it has been demonstrated for various static scenarios in the laboratory that contracting the quadriceps at knee flexion angles less than approximately 45° increases ACL strain through anterior pull of the patellar tendon on the tibia.[2,6,35] Contracting the hamstrings at knee flexion angles greater than approximately 30°, on the other hand, can decrease ACL strain and resist anterior tibial translation.[29,35] The findings from these studies suggest that the gender differences in activation levels during the athletic maneuvers might be increasing the load on the ACL and be placing women at greater risk for injuring the ACL.

It appears that having athletes perform a preplanned maneuver in the laboratory does not best replicate a true game-like situation in which the ACL is most likely to be damaged from a noncontact maneuver. Unanticipated maneuvers have been re-created in the laboratory using light guiding systems,[4,5,11,17,34] and it has been suggested that these maneuvers better replicate a true game-like scenario. Besier et al[4,5] showed that muscle activations increased approximately 10% to 20% and knee joint moments increased approximately 100% when going from a preplanned to unanticipated maneuver. Muscle activations also took on a generalized cocontraction pattern for the unanticipated maneuvers and a more selective pattern for the preplanned maneuvers. The authors proposed that these differences could be related to a reduction in the time to adequately prepare for the maneuvers.

A gender comparative study that simultaneously contrasts the lower limb neuromuscular response and the biomechanics of the hip, knee, and ankle during unanticipated running and crosscutting maneuvers does not exist in the literature. Therefore, the purpose of this study was to measure and compare the neuromuscular response of the lower limb, as well as the kinetics and kinematics of the knee, hip, and ankle, for unanticipated running and cutting maneuvers, with this article focusing on the crosscut and straight-running maneuvers and a companion article focusing on the side-cut maneuver.[20] Described in previous articles,[8,18,19] and in the companion side-cutting article,[20] principal component analysis (PCA) was used to analyze all the biomechanical and neuromuscular waveforms for both maneuvers. This multivariate analysis technique orthogonally decomposes an original data set (group of waveforms) and objectively captures important waveform features based on the variation within the original data set. These features, which are extracted from entire waveforms, get related to specific biomechanical or neuromuscular waveform characteristics, and then statistical hypothesis testing is used to compare groups based on these features.

The hypothesis for this study was that for both athletic maneuvers, biomechanical and neuromuscular differences would exist both between genders and between medial-lateral muscle sites and that these differences would help with understanding both the gender bias and the risk factors associated with noncontact ACL injuries.

METHODS

Subjects

The same elite adolescent soccer players (21 male, 17.0 ± 0.6 years; 21 female, 16.7 ± 1.0 years) described in the companion article[20] were analyzed in this article. All subjects were required to have no previous major lower limb injury and had to be symptom free from previous ankle sprains at the time of testing. The Research Ethics Board for Health and Medical Sciences at Dalhousie University approved this study, and consent was obtained from both the subjects and respective guardians.

Experimental Design

The methods for this study are described in detail in the companion side-cut article.[20] In summary, subjects were required to run down the runway of the laboratory at 3.5 ± 0.2 m/s, and approximately 0.5 seconds before planting the right leg on the force platform, a 3-light guiding system randomly cued the subjects to either side-cut (cut to the left) or crosscut (cut to the right) between 35° and 60° from the direction of travel or to run straight.

For the stance phase of all maneuvers, 3-dimensional joint angle (reported in the joint coordinate system) and net external joint moment waveforms (calculated using inverse dynamics and normalized to body weight) were compared between genders for the right leg. Ground-reaction forces and moments were captured using an AMTI force

TABLE 1
Approach Speed Data for Male and Female Subjects[a]

Cutting Characteristic, m/s	Male		Female		
	Mean	SD	Mean	SD	*P*
Crosscut approach speed	3.45	0.13	3.48	0.08	.44
Straight-run approach speed	3.55	0.11	3.53	0.12	.62

[a]Student *t* tests were used to test for differences between genders.

platform (Advanced Medical Technology Inc, Watertown, Mass) at 1000 Hz, and positional data for the pelvis, thigh, shank, and foot were captured using a series of infrared light–emitting diode markers and virtual markers with an Optotrak motion analysis system (Northern Digital Inc, Waterloo, Ontario, Canada) at 100 Hz.

Stance phase muscle activation patterns were collected at 1000 Hz for the medial gastrocnemius (MG) and lateral gastrocnemius (LG), the medial hamstrings (MH) and lateral hamstrings (LH), the vastus medialis (VM) and vastus lateralis (VL), and rectus femoris (RF) using an 8-channel surface EMG system (AMT-8 EMG, Bortec Inc, Calgary, Alberta, Canada). All activation waveforms were amplitude normalized to maximum voluntary isometric contractions for knee extension, knee flexion, hip flexion, and ankle plantar flexion.[18]

Data Analysis

All kinematic, kinetic, and EMG waveform data were processed and filtered in Matlab (MathWorks Inc, Natick, Mass), time normalized with 101 data points ranging from 0% (foot strike) to 100% (foot off), and then 3 to 5 trials were averaged together to generate ensemble average waveforms. For each specific waveform measure, the data were analyzed using PCA in Matlab and then statistically analyzed for gender or medial-lateral muscle site differences in Minitab (Minitab Inc, State College, Pa).

The companion article[20] and previous literature[8,18,19] describe the application of PCA to biomechanical and neuromuscular waveform data in detail. Principal component analysis can be summarized as an orthogonal transformation of the original waveform data into a new data set that allows waveform features such as overall waveform magnitudes, local magnitudes, phase shifts, and amplitudes to be identified based on the variability in the data. A separate PCA is applied to each different waveform measure, and then the individual waveforms get scored based on their similarity to the waveform features identified using PCA. To test for statistically significant differences between genders ($P < .05$), Student *t* tests were used on the anthropometric measures and on the PC scores from the joint angle, joint moment, and RF activation waveforms. A 2-factor mixed-model analysis of variance, with the repeated measure being muscle site (lateral and medial), was used for comparing the quadriceps, hamstrings, and gastrocnemii muscle groups. Post hoc pairwise comparisons tested for medial-lateral and gender differences using a Tukey adjustment ($P < .05$), with all analyses and statistical testing being performed in Matlab and Minitab.

RESULTS

Subject Demographics and Maneuver Approach Speeds

As previously reported in the side-cut companion article,[20] male subjects were 12.0 cm taller ($P < .0001$) and 8.81 kg heavier ($P < .0001$) than were female subjects, with no differences detected for age, body mass index, and years of playing experience. Approach speeds for both maneuvers did not differ between genders (Table 1).

TABLE 2
Interpretation and *P* Values for the Muscle Activation PC Waveforms During the Crosscut and Straight Run[a]

Muscle Model	PC	Interpretation	Crosscut: Gender Comparison *P*		Crosscut: Medial/Lateral Comparison *P*		Straight Run: Gender Comparison *P*		Straight Run: Medial/Lateral Comparison *P*	
			Medial	Lateral	Male	Female	Medial	Lateral	Male	Female
Gastrocnemii, LG and MG	PC1	Magnitude during early stance to midstance (approximately 0%-70%)	.43	<.001[b]	.97	.009[b]	.17	.002[b]	.62	.02[b]
	PC2	Magnitude during late stance (approximately 50%-100%)	.48	.40	.04[b]	1.0	.99	.03[b]	.86	.30
Hamstrings, LH and MH	PC1	Magnitude throughout stance	.05[b]	.006[b]	.91	1.0	.16	.01[b]	.16	.75
	PC3	Magnitude comparison between early stance and midstance	.07	.94	.28	.003[b]	.59	.07	.01[b]	.19
Quadriceps										
VL and VM	PC1	Magnitude throughout stance	.68	.89	.92	1.0	.01[b]	.02[b]	1.0	1.0
RF site only	PC1	Magnitude throughout stance	<.001[b]				.006[b]			

[a]Repeated-measures analysis of variance with Tukey adjusted post hoc pairwise comparisons was used to test for gender and medial/lateral site differences in principal component (PC) scores for the 3 muscle groups. For the rectus femoris (RF), Student *t* tests were used to test for gender differences in PC scores. LG, lateral gastrocnemius; LH, lateral hamstrings; MG, medial gastrocnemius; MH, medial hamstrings; VL, vastus lateralis; VM, vastus medialis.
[b]Statistically significant difference ($P < .05$).

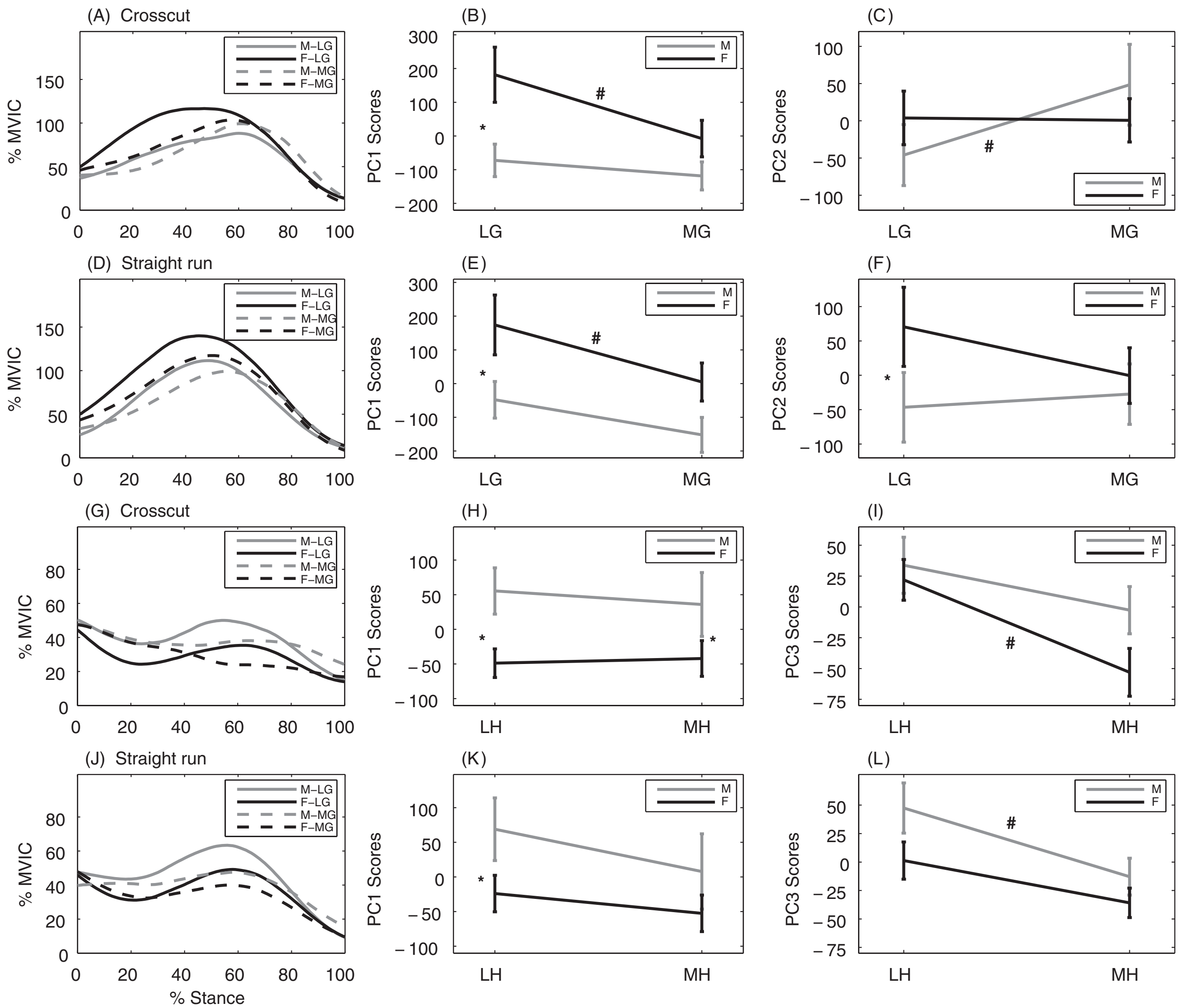

Figure 1. Male and female mean gastrocnemii and hamstring muscle activation waveforms for the stance phase of the crosscut and straight run and corresponding PC score means. Plots along the first and third row are for the crosscut, and plots along the second and fourth row are for the straight run. Left column includes group means of the MVIC normalized ensemble mean activation waveforms during stance for (A) LG and MG of the crosscut, (D) LG and MG of the straight run, (G) LH and MH of the crosscut, and (J) LH and MH of the straight run. Center and right column plots include male and female PC score group means with standard error of the means for (B) gastrocnemii PC1 (magnitude during early stance to midstance of crosscut), (C) gastrocnemii PC2 (magnitude during late stance of crosscut), (E) gastrocnemii PC1 (magnitude during early stance to midstance of straight run), (F) gastrocnemii PC2 (magnitude during late stance of straight run), (H) hamstrings PC1 (magnitude throughout stance of crosscut), (I) hamstrings PC3 (magnitude/shape during early stance and midstance of crosscut), (K) hamstrings PC1 (magnitude throughout stance of straight run), and (L) hamstrings PC3 (magnitude/shape during early stance and midstance of straight run). For the PC score plots, * indicates a significant gender difference, and # indicates a significant medial-lateral muscle site difference ($P < .05$). LG, lateral gastrocnemius; LH, lateral hamstrings; MG, medial gastrocnemius; MH, medial hamstrings; MVIC, maximum voluntary isometric contractions; PC, principal components.

Electromyography

For each separate PCA of the muscle activation waveforms for both maneuvers, at least 91.2% of the total waveform variance was captured and described by the first 3 PCs. The overall magnitude of the muscle activation waveforms was generally captured by PC1, with large activation magnitudes corresponding to large PC scores. More subtle and less discriminatory features were captured by PC2 and PC3.

Gastrocnemii Activation Waveforms

For both the crosscut and straight run, the overall gastrocnemii activation magnitude during early stance to midstance

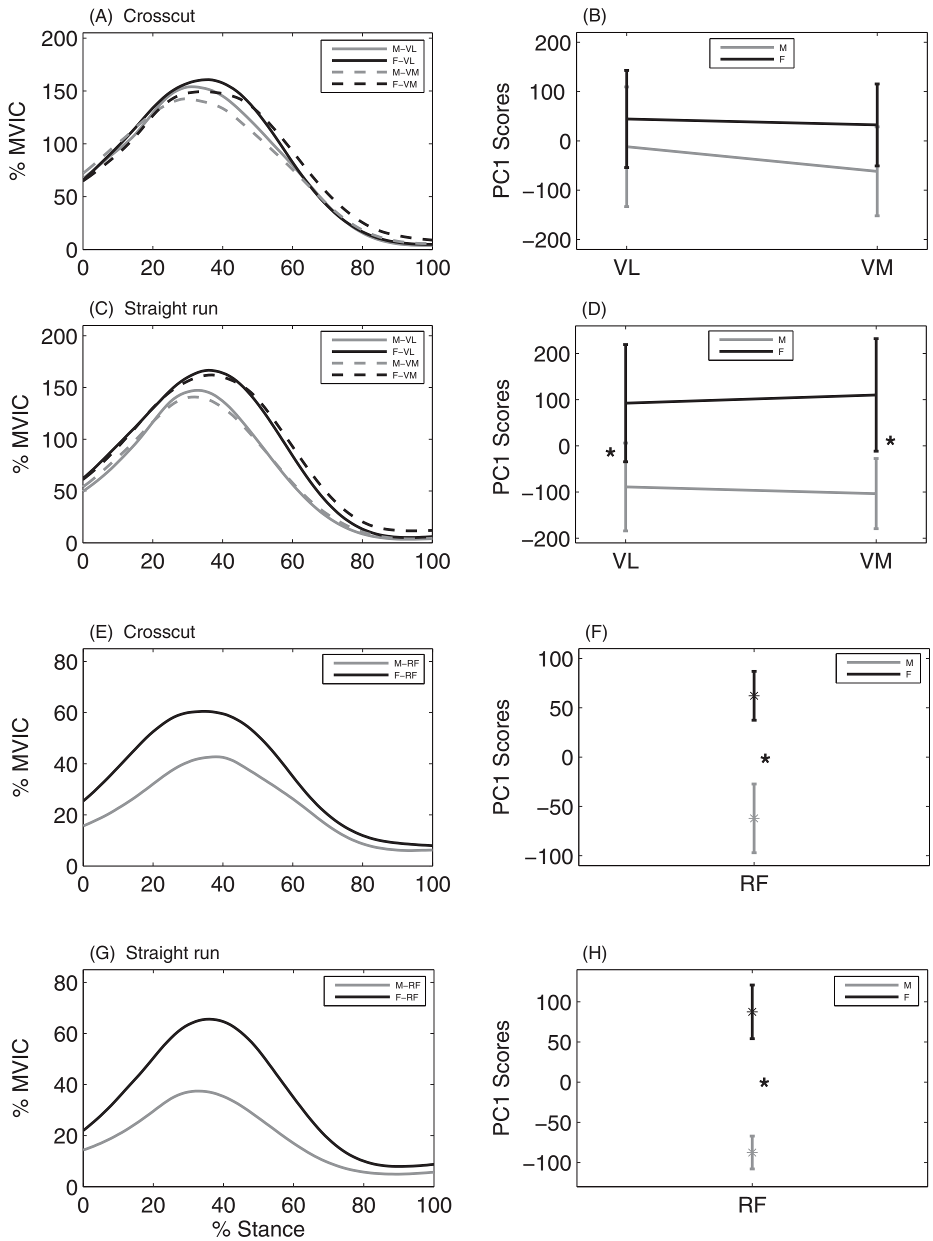

Figure 2. Male and female mean quadriceps muscle activation waveforms for the stance phase of the crosscut and straight run and corresponding PC score means. Plots along the first and third row are for the crosscut, and plots along the second and fourth row are for the straight run. Left column includes group means of the MVIC normalized ensemble mean activation waveforms during stance for (A) VL and VM of the crosscut, (C) VL and VM of the straight run, (E) RF of the crosscut, and (G) RF of the straight run. Right column plots correspond to the adjacent waveform plots in the left column and include male and female PC1 score (magnitude throughout stance) group means with standard error of the means for the (B) VL and VM of the crosscut, (D) VL and VM of the straight run, (F) RF of the crosscut, and (H) RF of the straight run. For the PC score plots, * indicates a significant gender difference, and # indicates a significant medial-lateral muscle site difference ($P < .05$). MVIC, maximum voluntary isometric contractions; PC, principal components; RF, rectus femoris; VL, vastus lateralis; VM, vastus medialis.

(approximately 0%-70%) was captured by PC1 (Table 2 and Figures 1 A and D). The LG of female subjects was activated to a higher percentage of maximum voluntary isometric contractions than was the MG of female subjects (crosscut, $P = .009$; straight run, $P = .02$) and more activated than was the LG of their male counterparts (crosscut, $P < .001$; straight run, $P = .002$) during the early stance to midstance portion of both maneuvers (Figures 1 B and E). The mediolateral imbalance evident in female athletes was not present in the gastrocnemii of the male subjects for both maneuvers (crosscut, $P = .97$; straight run, $P = .62$). For the later half of the stance phase (approximately 50%-100%) and in male subjects only, the MG was more activated than was the LG during the crosscut (PC2, $P = .04$)

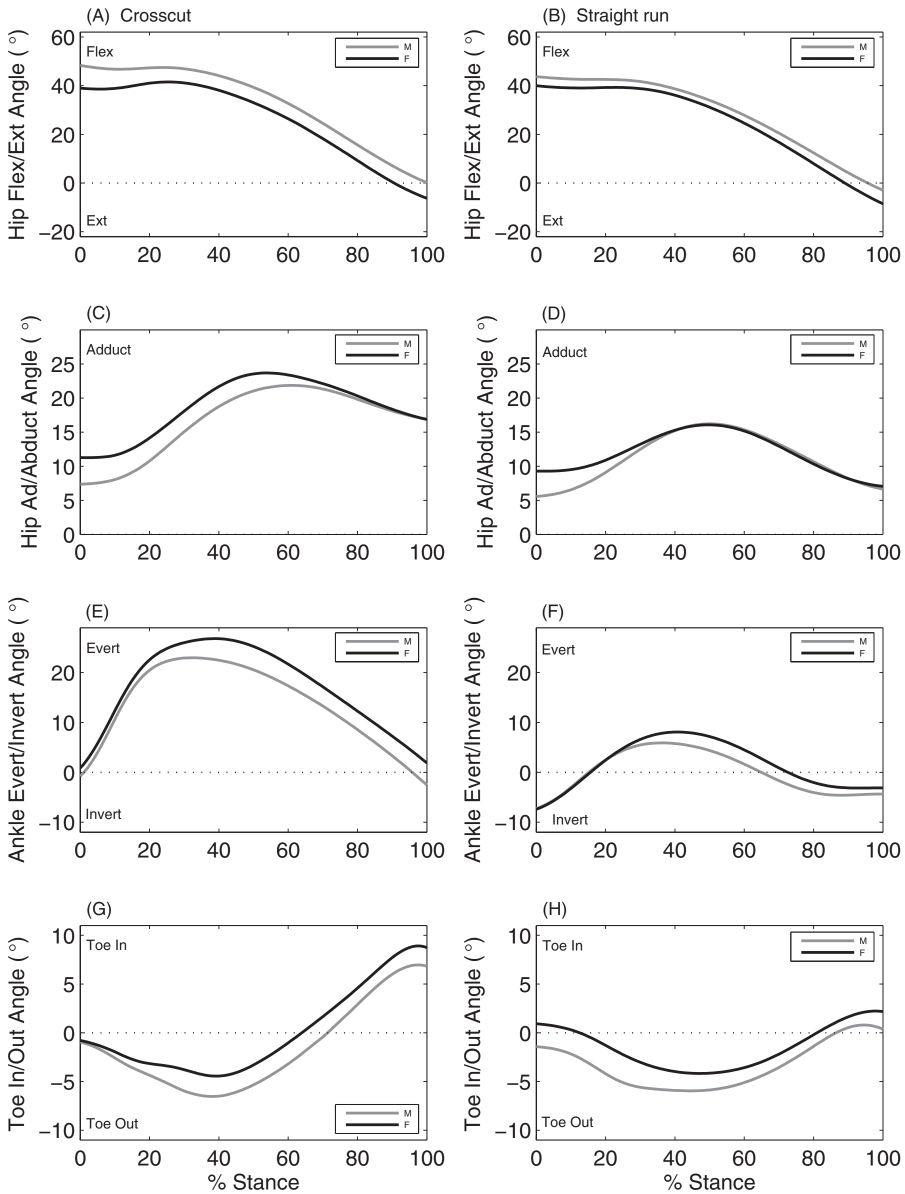

Figure 3. Male and female mean joint angle waveforms for the stance phase of the crosscut and straight run. Left column corresponds to crosscut, and the right column corresponds to straight run. (A) and (B) Graphs represent hip flexion/extension, (C) and (D) graphs represent hip adduction/abduction, (E) and (F) graphs represent ankle eversion/inversion, and (G) and (H) graphs represent toe-in/toe-out angle.

(Figure 1C). For the straight run only, the female LG was activated at a greater magnitude than was the male LG (PC2, P = .003) (Figure 1F).

Hamstrings Activation Waveforms

Female subjects demonstrated lower LH (P = .006) and MH (P = .05) activity compared to male subjects throughout the duration of stance (PC1) for the crosscut (Table 2 and Figures 1 G and H). Also for the crosscut, the female LH was less active than was their MH during early stance and more active than was the MH during midstance (PC3, P = .003) (Figures 1 G and I). Female subjects had lower LH activity (P = .01) compared with male subjects for the straight run; however, a difference between genders was not significant at the MH site (P = .16) (Figures 1 J and K), and this may have been a result of the sample size and inadequate statistical power (.178). Also for the straight run, the MH of the male subjects was activated at relatively the same magnitude during early stance and midstance, whereas the LH was activated at a greater magnitude during midstance compared to the early stance (PC3, P = .01) (Figures 1 J and L).

Quadriceps Activation Waveforms

For the simultaneous analysis of the VM and VL, the only difference captured was a gender difference during

TABLE 3
Interpretation, Gender Means, Standard Error of the Means (SEM), and *P* Values for the Kinematic and Kinetic PC Waveforms During the Crosscut and Straight Run[a]

			Gender Comparisons of PC									
			Crosscut					Straight Run				
			Male		Female			Male		Female		
Gait Measure	PC	Biomechanical Interpretation	Mean	SEM	Mean	SEM	*P*	Mean	SEM	Mean	SEM	*P*
Joint angles												
Hip flexion/extension	PC1	Magnitude throughout stance	32.8	17.3	–32.8	18.2	.01[b]	17.7	16.8	–17.7	15.7	.13
Hip adduction/abduction	PC2	Amplitude/range of motion throughout stance	–5.9	4.8	5.9	4.5	.08	–5.7	3.3	5.7	2.9	.01[b]
Ankle eversion/inversion	PC1	Magnitude throughout stance	–18.0	6.7	18.0	8.6	.002[b]	–8.3	8.8	8.3	9.2	.20
Ankle toe in/out	PC1	Magnitude throughout stance	8.5	6.9	–8.5	7.5	.10	9.1	6.2	–9.1	5.8	.04[b]
Knee flexion/extension	PC1	Magnitude throughout stance	–10.8	16.6	10.8	14.8	.34	–6.1	17.8	6.1	11.9	.57
Joint moments												
Hip flexion/extension	PC1	Magnitude throughout stance	1.70	0.87	–1.70	0.63	.003[b]	1.59	0.85	–1.59	0.59	.004[b]
Hip adduction/abduction	PC1	Magnitude throughout stance	–1.02	0.64	1.02	0.67	.03[b]	–0.54	0.62	0.54	0.63	.23
Hip internal/external rotation	PC1	Magnitude throughout stance	–0.41	0.41	0.41	0.31	.12	–0.56	0.42	0.56	0.30	.04[b]
Knee flexion/extension	PC3	Magnitude during early stance (approximately 0%-12%)	0.43	0.28	–0.43	0.29	.04[b]	0.36	0.19	–0.36	0.20	.01[b]
Knee adduction/abduction	PC1	Magnitude throughout stance	–0.87	0.54	0.87	0.56	.03[b]	–0.63	0.54	0.63	0.50	.10

[a] *t* tests were used to test for gender differences in the principal component (PC) scores for the kinematic and kinetic waveforms.
[b] Statistically significant difference ($P < .05$).

the straight run (Figures 2 C and D), with female subjects having greater activation magnitudes than did male subjects throughout the duration of stance for both the VM (P = .01) and VL (P = .02). Rectus femoris activity in female subjects was also greater than that in male subjects for both the crosscut ($P < .001$) (Figures 2 E and F) and straight run (P = .006) (Figures 2 G and H) maneuvers.

Kinematics

The most prominent kinematic differences between male and female subjects were at the hip followed by the ankle, with no differences detected at the knee for both maneuvers (Table 3 and Figure 3). For all kinematic waveform measures, the first 3 PCs captured a minimum of 96.0% of the total waveform variance. To aid with the interpretation of the PCA results, Figure A1 in Appendix A (available in the online version of this article at http://ajsm.sagepub.com/cgi/content/full/35/11/1901/DC1/) includes the kinematic and kinetic PC waveforms for the measures reported in Table 3.

At the hip and similar to the side-cut maneuver,[20] male subjects demonstrated larger flexion angles than did female subjects for the duration of the crosscut stance phase (PC1, P = .01) (Figure 3A). With respect to hip adduction angle, a gender difference was significant for only the straight run. Male subjects landed with a smaller hip adduction angle than did female subjects and then went into a more adducted position as stance progressed, whereas female athletes tended to maintain a more constant hip adduction angle as stance progressed (PC2, P = .01) (Figure 3D).

At the ankle, kinematic differences were detected for both maneuvers (Table 3 and Figure 3). Female subjects demonstrated greater ankle eversion angles than did male subjects throughout stance (PC1) for only the crosscut maneuver (P = .002) (Figure 3E). Male subjects performed the straight run with a larger toe-out angle for the entire stance phase (PC1) than did female subjects (P = .04) (Figure 3H). At the knee and for both maneuvers, no gender differences were captured for knee flexion angle (crosscut, P = .34; straight run, P = .57).

Kinetics

Differences between genders in net external joint moments were identified at the hip and knee with no differences identified at the ankle (Table 3 and Figure 4). For both

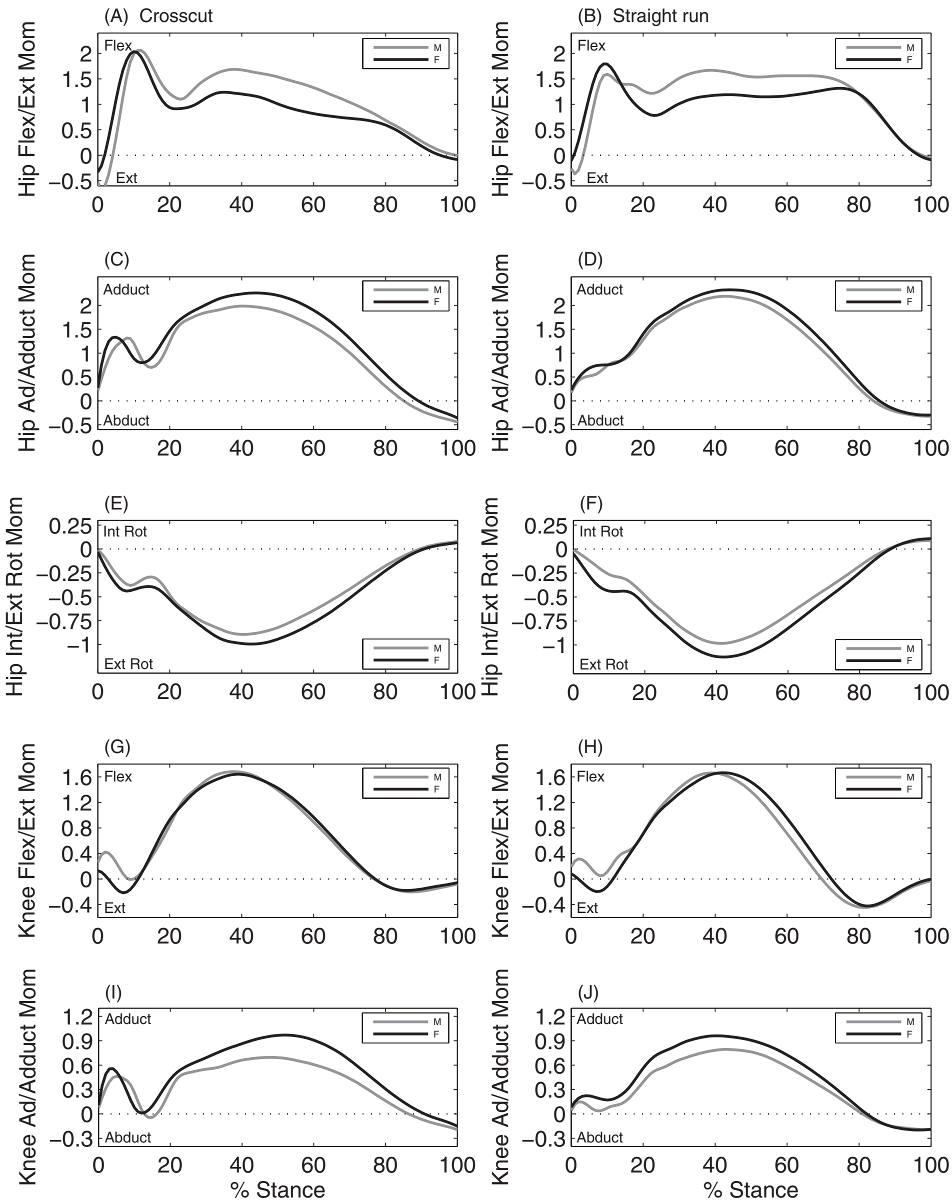

Figure 4. Male and female mean joint moment waveforms (normalized to body weight, Nm/kg) for the stance phase of the crosscut and straight run. Left column corresponds to crosscut, and the right column corresponds to straight run. (A) and (B) Graphs represent hip flexion/extension, (C) and (D) graphs represent hip adduction/abduction, (E) and (F) graphs represent hip internal/external rotation, (G) and (H) graphs represent knee flexion/extension, and (I) and (J) graphs represent knee adduction/abduction moment.

maneuvers, the first 4 PCs of each waveform measure explained at least 91.4% and 97.2% of the variation in the knee and ankle moment waveforms, respectively. For the hip moments, the first 4 PCs described at least 86.6% of the variation in moment waveforms.

Male subjects tended to land with a greater hip extension moment than did female subjects. As early stance progressed, individuals experienced a flexion moment, with male subjects having the smaller magnitude than did female subjects for both maneuvers (PC1). For the remainder of stance, however, male subjects experienced a greater overall hip flexion moment than did the female athletes (PC1; crosscut, $P = .003$; straight run, $P = .004$) (Figures 4 A and B). With respect to the frontal plane hip moment, females generated a greater hip adduction moment throughout stance for the crosscut ($P = .03$) (Figure 4C), with no hip adduction moment differences detected for the straight run ($P = .23$) (Figure 4D). Hip external rotation moment differences were evident for the straight run ($P = .04$) (Figure 4F) but not the crosscut ($P = .12$) (Figure 4E), with female subjects producing a greater overall hip external rotation moment than did male subjects during the stance phase of the straight run.

Differences between genders in knee flexion moment (PC3) for the crosscut and straight run (Figures 4 G and H) and in knee adduction moment (PC1) for only the crosscut were also identified (Figure 4I). During early stance (approximately 0%-12%), female subjects tended to generate a knee extension moment, whereas male subjects tended to produce a knee flexion moment for both maneuvers (crosscut, $P = .04$; straight run, $P = .01$). With respect to the knee adduction moment and for the crosscut only, female subjects produced a larger knee adduction moment throughout stance ($P = .03$) (Figure 4I).

DISCUSSION

Neuromuscular and biomechanical differences between male and female elite adolescent soccer players were identified during both an unanticipated straight-run and crosscut maneuver. Many of these differences not only were able to be related to noncontact ACL injury risk factors and the gender bias associated with the injury but were also similar to many of the differences reported for the unanticipated side-cut maneuver in the companion article.[20]

For both the crosscut and straight run, female subjects demonstrated greater LG activity than did male subjects during early stance to midstance, and female athletes had a medial-lateral gastrocnemii activation imbalance (LG > MG) that was not present in male athletes. It is difficult to conclude whether these activation differences place female athletes at greater risk for ACL injury or whether the differences are a compensatory mechanism aimed at increasing joint stability in the female knee, which tends to be more lax than is the male knee.[36] Studies have shown that contracting the gastrocnemii in static situations can increase ACL strain.[10,32] Although further investigations into the role of the gastrocnemii at the knee are needed, it is a possibility that during the dynamic maneuvers, female athletes require more LG activity to increase the overall stiffness of their more lax knee joint; in doing so, they may be placing the ACL under greater stress and thereby might possibly be increasing the risk of injury to this ligament.

Similar to the side-cut maneuver[20] and compared with the male subjects, female subjects demonstrated greater RF activity throughout stance for both the unanticipated crosscut and straight run. For the straight run only, female subjects also had greater VL and VM activity than did male subjects. With respect to the hamstring muscle sites, female subjects had reduced LH and MH activity levels compared with male subjects through stance for both maneuvers; however, the MH site gender difference during the straight run was not statistically significant ($P = .16$). In general, these findings are in agreement with previous studies that also reported female athletes have increased quadriceps activity[21,37] and reduced hamstrings activity[21] compared with male athletes during a preplanned side-cut, crosscut, and/or straight run. It has been demonstrated under static situations that contracting the quadriceps at knee flexion angles less than approximately 45° can increase ACL strain,[29,35] and contracting the hamstrings at knee flexion angles greater than approximately 30° can reduce ACL strain.[2,35] For the athletic maneuvers in this study, the increased activation of the quadriceps in female subjects may not necessarily correspond to increased quadriceps force, but the combination of the increased quadriceps activity and decreased hamstring activity in the female athletes certainly increases the likelihood of greater knee anterior shear forces and hence possibly increased ACL strain in the female subjects during the athletic maneuvers. As well, muscle contraction is important for knee joint stability,[14,38] and the reduction in hamstring activity observed in female athletes might also serve as a potential risk factor for ACL injuries, although further studies in this area are recommended.

The medial-lateral activation imbalances evident in only the gastrocnemii and hamstrings and not in the quadriceps could be related to the location at which these muscles attach and act as they cross the knee joint. Unlike the vastii muscles that attach centrally through the patellar tendon, the hamstrings and gastrocnemii have medial and lateral attachment sites on the tibia and femur, respectively, giving them greater moment arm lengths in the transverse and frontal plane of the knee. Selective activation of either the MG or LG or hamstring sites would therefore tend to have a more significant influence than would the quadriceps in controlling the greater internal-external rotation or adduction-abduction movements and moments experienced during the athletic maneuvers.

With respect to lower limb biomechanics, previous gender comparative studies of crosscutting and running maneuvers have focused primarily on the mechanics of the knee,[21,28] with only 1 study including the hip.[9] In our study, the most prominent kinematic difference between genders for the 3 joints was at the hip, with female athletes generating a smaller hip flexion angle than did male athletes for the unanticipated crosscut only, similar to the side-cut maneuver in the companion article.[20] It has been noted in studies focusing on landing maneuvers[13,39] that smaller knee and hip angles can be a risk factor for ACL injuries. The peak impact posterior ground-reaction force during landing has been shown to be significantly correlated with hip flexion (B. Yu and W. E. Garrett, unpublished data, 2005), and this posterior force affects the peak proximal tibial anterior force, which is the major ACL loading mechanism.[23] Yu et al[40] were also able to demonstrate that ground-reaction force, proximal tibial shear force, and ACL loading are correlated, supporting the notion that reduced hip flexion angles can put the ACL at greater risk of being injured.

For the unanticipated crosscut maneuver, moment differences between genders were captured at the knee and hip throughout stance and during early stance when the injury generally takes place.[7] The greater hip flexion moment observed in male athletes might partially explain the higher LH and MH activity experienced by males compared with females during the crosscut. The increased hamstring activity may be necessary to increase the internal hip extension moment to balance the greater net hip flexion moment in males. A further benefit of the increased hamstring activity could be at the knee, with the increased activity enhancing joint stability and possibly acting as an agonist for the ACL, providing the posterior pull on the tibia to decrease the strain on the ACL[29,35] during the athletic maneuvers.

In contrast to the differences in hip flexion moment identified between genders, female athletes demonstrated greater hip and knee adduction moments throughout the stance phase of the crosscut than did male athletes. Although it remains unclear as to whether a greater hip adduction moment is a risk factor for ACL injury, the greater knee adduction moment in male subjects could be increasing the load on the ACL. It has been shown using cadaveric specimens that an adduction moment at the knee combined with an anterior tibial force can actually increase the loading on the ACL in an additive manner.[23] With respect to the early stance moment differences that were evident for the side-cut,[20] crosscut, and straight run, it remains unclear as to whether these gender differences have a contributing role toward the higher prevalence of ACL injuries in female compared with male athletes, therefore warranting further investigations.

Although no kinetic differences were detected at the ankle, kinematic differences were identified at the ankle. Female soccer players demonstrated greater ankle eversion angles than did male soccer players throughout the stance phase of the crosscut, and this agrees with findings from a stop-jump, unanticipated side-cut study by Ford et al.[11] Excessive subtalar joint pronation has been described as a possible ACL injury risk factor[3] because ankle eversion is coupled with tibial internal rotation,[24,30] a motion that the ACL has a significant role in resisting and controlling.[12,23]

Similar to those described in the companion article,[20] limitations do exist both with respect to the variability in how the subjects performed the cutting maneuvers and in the inability to quantify the biomechanical magnitude of the gender and/or mediolateral differences identified using PCA. Although approach speed and angle of cut were both diligently controlled in the study, subjects were instructed to perform the maneuvers in a manner that felt natural to them. It was evident by observing the athletes during testing that there were slight variations in how the athletes carried out the maneuvers, and although several differences were successfully captured between the male and female subjects, there were some comparisons that lacked adequate statistical power. The lack of power may have been related to the intersubject variability while performing the maneuvers or to the sample size, although the sample size was relatively large compared with those of similar studies that have analyzed the neuromuscular response, joint kinematics, and joint kinetics for various athletic maneuvers. As well, despite the high degree of variability in the waveforms and inability to quantify the differences in the units in which the waveforms were described, it was encouraging to see that the application of PCA not only described the majority of the waveform variability with only a few PCs or eigenvectors for each waveform measure but also successfully captured differences that have not been previously identified in the literature.

CONCLUSION

Biomechanical and neuromuscular differences between male and female elite adolescent soccer players were identified for unanticipated athletic maneuvers, with many of the differences being used to improve on the current understanding of noncontact ACL injuries and the gender bias associated with this injury. Differences between genders, particularly for the LG and RF activation patterns and hip flexion moment, were similar for the 2 maneuvers described in this study and for the side-cut maneuver reported in the companion article.[20] This comprehensive study also analyzed unanticipated maneuvers, which are thought to more closely replicate a true game-like situation in which the ACL is most likely to be damaged. This also represents one of the first cutting-related studies to simultaneously compare kinematics and kinetics of the hip, knee, and ankle and neuromuscular activation patterns of the medial and lateral muscle sites surrounding the knee.

ACKNOWLEDGMENT

The authors thank NSERC and Nike Inc, Sports Research Laboratory (Beaverton, Ore) for financial support and Soccer Nova Scotia for their support and help in subject recruitment.

REFERENCES

1. 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.
2. 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.
3. Beckett ME, Massie DL, Bowers KD, Stoll DA. Incidence of hyperpronation in the ACL injured knee: a clinical perspective. *J Athl Train*. 1992;27(1):58-62.
4. Besier TF, Lloyd DG, Ackland TR. Muscle activation strategies at the knee during running and cutting maneuvers. *Med Sci Sports Exerc*. 2003;35(1):119-127.
5. 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(7):1176-1181.
6. 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.
7. Boden BP, Dean GS, Feagin JA Jr, Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23(6):573-578.
8. 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(2-3):201-217.
9. Ferber R, Davis IM, Williams DS. Gender differences in lower extremity mechanics during running. *Clin Biomech (Bristol, Avon)*. 2003;18(4):350-357.
10. Fleming BC, Renstrom PA, Ohlen G, et al. The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *J Orthop Res*. 2001;19(6):1178-1184.
11. 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.
12. Furman W, Marshall JL, Girgis FG. The anterior cruciate ligament: a functional analysis based on postmortem studies. *J Bone Joint Surg Am*. 1976;58(2):179-185.
13. 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(2):182-192.
14. Goldfuss AJ, Morehouse CA, LeVeau BF. Effect of muscular tension on knee stability. *Med Sci Sports*. 1973;5(4):267-271.
15. 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(3):141-150.
16. 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(2):299-311.

17. 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(3):314-322.
18. 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(4):365-378.
19. 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*. 2007;40(8):1754-1761.
20. Landry SC, McKean KA, Hubley-Kozey CL, Stanish WD, Deluzio KJ. Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver. *Am J Sports Med*. 2007;35(11):1888-1900.
21. 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.
22. 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.
23. 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.
24. McClay I, Manal K. Coupling parameters in runners with normal and excessive pronation. *J Appl Biomech*. 1997;13(1):109-124.
25. McLean SG, Huang X, Su A, van den Bogert AJ. Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. *Clin Biomech (Bristol, Avon)*. 2004;19(8):828-838.
26. 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(8):863-870.
27. 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.
28. 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(7):959-968.
29. 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(2):231-237.
30. Nigg BM, Cole GK, Nachbauer W. Effects of arch height of the foot on angular motion of the lower-extremities in running. *J Biomech*. 1993;26(8):909-916.
31. 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(2):154-162.
32. O'Connor JJ. Can muscle co-contraction protect knee ligaments after injury or repair? *J Bone Joint Surg Br*. 1993;75(1):41-48.
33. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med*. 2004;32(4):1002-1012.
34. 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(10):1022-1031.
35. 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.
36. 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(3):312-319.
37. 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.
38. Solomonow M, Baratta R, Zhou BH, et al. The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. *Am J Sports Med*. 1987;15(3):207-213.
39. 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(1):9-14.
40. Yu B, Chappell JD, Garrett WE. Responses to letters to the editor. *Am J Sports Med*. 2006;34:312-315.
41. Yu B, Kirkendall DT, Garrett WE. Anterior cruciate ligament injuries in female athletes: anatomy, physiology, and motor control. *Sports Med Arthrosc*. 2002;10(1):58-68.