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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

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
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 cutting 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. Described in previous articles and in the companion side-cutting article, principal component analysis (PCA) was used to analyze all the biomechanical and neuromuscular waveform features 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 were analyzed in this article. All subjects were required to have no previous major lower limb injury and 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. 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...
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, hip flexion, and ankle plantar flexion.²⁸

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 article²⁰ and previous literature⁸,¹⁸,¹⁹ 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 gastrocnemius 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 1

<table>
<thead>
<tr>
<th>Characteristic, m/s</th>
<th>Male Mean</th>
<th>SD</th>
<th>Female Mean</th>
<th>SD</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crosscut approach speed</td>
<td>3.45</td>
<td>0.13</td>
<td>3.48</td>
<td>0.08</td>
<td>.44</td>
</tr>
<tr>
<td>Straight-run approach speed</td>
<td>3.55</td>
<td>0.11</td>
<td>3.53</td>
<td>0.12</td>
<td>.62</td>
</tr>
</tbody>
</table>

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

### TABLE 2

<table>
<thead>
<tr>
<th>Muscle Model</th>
<th>PC Interpretation</th>
<th>Crosscut</th>
<th>Straight Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gastrocnemii, LG and MG</td>
<td>Magnitude during early stance to midstance (approximately 0%-70%)</td>
<td>.43</td>
<td>.17</td>
</tr>
<tr>
<td>Hamstrings, LH and MH</td>
<td>Magnitude comparison between early stance and midstance</td>
<td>.07</td>
<td>.16</td>
</tr>
<tr>
<td>Quadriceps</td>
<td>Magnitude throughout stance</td>
<td>.68</td>
<td>.01</td>
</tr>
</tbody>
</table>

*Repeated-measures analysis of variance with Tukey adjusted post hoc pairwise comparisons was used to test for gender and medial-lateral 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. Statistically significant difference (P < .05).*
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)
For the straight run only, the female LG was activated at a greater magnitude than was the male LG ($P = 0.003$) (Figure 1F).

Hamstrings Activation Waveforms

Female subjects demonstrated lower LH ($P = 0.006$) and MH ($P = 0.05$) 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, $P = 0.003$) (Figures 1 G and I). Female subjects had lower LH activity ($P = 0.01$) compared with male subjects for the straight run; however, a difference between genders was not significant at the MH site ($P = 0.16$) (Figures 1 J and K), and this may have been a result of the sample size and inadequate statistical power (0.178). 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, $P = 0.01$) (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...
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://ajs.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
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 4A 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 gastrocnemius 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 activity1,17 and reduced hamstrings activity21 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 strain28,35 and contracting the hamstrings at knee flexion angles greater than approximately 30° can reduce ACL strain.28,35 For the athletic maneuvers in this study, the increased activation of the quadriceps in female subjects may not necessarily correspond to increased quadriiceps 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.7 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 maneuvers13,39 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.22 Yu et al40 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 ACL28,35 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. With respect to the early stance moment differences that were evident for the side-cut, 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. Excessive subtalar joint pronation has been described as a possible ACL injury risk factor because ankle eversion is coupled with tibial internal rotation, a motion that the ACL has a significant role in resisting and controlling.

Similar to those described in the companion article, 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. 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

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REFERENCES


