Effect of Gender and Defensive Opponent on the Biomechanics of Sidestep Cutting

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ABSTRACT

MCLEAN, S. G., S. W. LIPFERT, and A. J. VAN DEN BOGERT. Effect of Gender and Defensive Opponent on the Biomechanics of Sidestep Cutting. Med. Sci. Sports Exerc., Vol. 36, No. 6, pp. 1008–1016, 2004. Purpose: Anterior cruciate ligament (ACL) injuries often occur in women during cutting maneuvers to evade a defensive player. Gender differences in knee kinematics have been observed, but it is not known to what extent these are linked to abnormal neuromuscular control elsewhere in the kinetic chain. Responses to defense players, which may be gender-dependent, have not been included in previous studies. This study determined the effects of gender and defense player on entire lower extremity biomechanics during sidestepping. Methods: Eight male and eight female subjects performed sidestep cuts with and without a static defensive opponent while 3D motion and ground reaction force data were recorded. Peak values of eight selected motion and force variables were, as well as their between-trial variabilities, submitted to a two-way (defense × gender) ANOVA. A Bonferroni-corrected alpha level of 0.003 denoted statistical significance. Results: Females had less hip and knee flexion, hip and knee internal rotation, and hip abduction. Females had higher knee valgus and foot pronation angles, and increased variability in knee valgus and internal rotation. Increased medial ground reaction forces and flexion and abduction in the hip and knee occurred with the defensive player for both genders. Conclusions: A simulated defense player causes increased lower limb movements and forces, and should be a useful addition to laboratory protocols for sidestepping. Gender differences in the joint kinematics suggest that increased knee valgus may contribute to ACL injury risk in women, and that the hip and ankle may play an important role in controlling knee valgus during sidestepping. Consideration of the entire lower extremity contributes to an understanding of injury mechanisms and may lead to better training programs for injury prevention. Key Words: ANTERIOR CRUCIATE LIGAMENT, INJURY, LOWER LIMB KINEMATICS, SIMULATED DEFENSE, FEMALES, NEUROMUSCULAR CONTROL

Rupture of the anterior cruciate ligament (ACL) in the knee is one of the most common and potentially traumatic sports-related knee joint injuries. Approximately 80,000 ACL injuries occur annually within the United States, with 50,000 requiring surgical reconstruction (10). Sustaining an ACL injury also predisposes an individual to the risk of significant long-term debilitation, such as in the case of osteoarthritis (9). The success of reconstructive surgery in preventing secondary OA is still debated (16), indicating the potential for permanent disability in a large group of individuals.

Typically, ACL injury occurs as a result of a noncontact episode (1,10), during the landing or stance phase of “high-risk” sporting postures such as sidestepping (3,7,19). These movements are key offensive strategies in sports such as basketball, team handball, and soccer and commonly incorporate a sudden deceleration phase on impact, accompanied by a rapid speed and/or directional change to evade an oncoming defensive opponent (19,21).

In the game situation, execution of sidestepping maneuvers occurs with both a temporal and spatial randomness that deems “on-site” analyses of lower limb motion and function virtually impossible. Instead, analyses are commonly conducted in the laboratory setting, where movement execution can be more effectively controlled and evaluated. Typically in these instances, sidestepping tasks are performed such that the stance, or contact phase of the maneuver occurs on a force plate, within the field of view a 3D high-speed video system, with the ensuing 3D force and video data providing the kinematic and kinetic descriptors of the movement. Using such an approach, an abundance of biomechanical data has been generated for sidestep cutting maneuvers, including descriptions of lower limb joint kine-
matics (19,22), kinetics (3,4), and muscle activation patterns (5,7). Recently, there has been an increased focus on gender differences in these parameters, to elucidate the causes of the higher incidence of ACL injuries in women. The gender differences observed in knee joint kinematics and forces during these movements are thus viewed as important contributors to ACL injury potential (7,19).

A concern with lab-based assessments of sport movements has been the extent to which they accurately reflect the game environment. Besier and associates (4) have acknowledged this potential disparity, finding that unanticipated execution of sidestepping maneuvers produced significant increase in external varus/valgus and internal/external knee moments compared with movements that less closely reflected game play. Another limitation of previous laboratory-based investigations of sidestepping is the absence of a defensive opponent. With the sidestep primarily being an evasive maneuver, the inclusion of a defensive opponent may be an important factor in determining how the movement is performed. It is not known to what extent this could have affected the conclusions of previous lab-based analyses of sidestepping. Specifically, the conclusions on gender differences would be affected if there were a gender disparity in the response to a more game-like test condition.

Another limitation of most studies examining the potential links between hazardous sporting movements and ACL injury is their exclusive focus on the biomechanics of the knee joint. Injury to the ACL ultimately occurs as a result of knee loads that cannot be supported by bony structures and muscles, thus leading to large ligament loads. It is increasingly recognized, however, that extreme knee loading scenarios may be potentiated through abnormal neuromuscular control elsewhere in the lower extremity. Hypotheses have been formulated related to gender differences in transverse plane and frontal plane hip rotations, and in rearfoot pronation (12,31). There are, however, little or no data to support these theories. A proper understanding of complete ACL injury mechanisms will require a biomechanical analysis of the entire lower extremity during actual sport movements.

The purposes of the current study therefore were:
1) To determine whether inclusion of a simulated defensive opponent promoted differences in stance phase lower limb joint kinematics and ground reaction forces during sidestep execution.
2) To determine whether gender differences in the above variables were evident during sidestepping, and to determine the extent to which these differences were influenced by the presence of a defensive opponent.

METHODS

Sixteen (eight female, eight male) subjects had 3D lower limb joint rotation and 3D ground reaction force data recorded during the execution of sidestep cutting maneuvers. Previous research comparing male and female knee kinematics for sidestepping found that the ratio of within group to between group differences was 0.73 (19). Submitting this figure to a two-way repeated measures power analysis revealed that a minimum of six subjects per group (male and female) would be necessary to generate a statistical power of 0.8 in the current study. The research was approved through the Institutional Review Board of the Cleveland Clinic Foundation and written informed consent for all subjects was obtained before testing. Subject inclusion in the study was based on no history of operable lower limb joint injury and a proficiency in performing sidestepping maneuvers. Subject characteristics are summarized in Table 1.

Sixteen reflective markers (Fig. 1) were secured to the limb under investigation with strapping tape, and attachment sites were shaved to minimize marker movement. To further minimize marker movement errors as a result of impact, attachment over areas of large muscle mass was avoided. A six-camera video system was calibrated to obtain 3D coordinates of these markers at 240 frames per second (Motion Analysis Corp., Santa Rosa, CA). A static trial was first recorded with the subject standing. The medial femoral condyle and medial and lateral malleoli markers were removed before the movement trials.

For each subject, hip, knee, and ankle joint 3D kinematic and 3D ground reaction force data were recorded for the

| TABLE 1. Mean subject characteristics by gender. |
|-----------------|-----------------|-----------------|
| Characteristic  | Male ± SD        | Female ± SD      |
|-----------------| (N = 8)          | (N = 8)          |
| Age (yr)        | 21.4 ± 3.2       | 22.2 ± 3.8       |
| Height (cm)     | 177.5 ± 8.3      | 167.3 ± 6.5      |
| Weight (kg)     | 73.1 ± 3.8       | 64.1 ± 5.0       |
| Femur length (cm)† | 40.6 ± 2.5     | 37.9 ± 2.6       |
| Tibia length (cm)† | 38.2 ± 2.3     | 36.9 ± 3.4       |

† Femur length is taken from greater trochanter to lateral knee joint space.
* Tibia length is taken from the lateral knee joint space to the lateral malleolus.
right (contact) leg during the stance phase of 20 sidestep cutting maneuvers. The right leg was required to contact a force plate (AMTI OR6-5 #4048, Advanced Mechanical Technology, Inc.), within the field of view of the video analysis system. Sidestepping maneuvers were performed under two conditions, with (D) and without (ND) a simulated defensive opponent. Ten trials were performed in each condition and the order of the conditions was randomized for each subject. The defensive opponent was simulated using a plastic skeleton positioned 20 cm behind the force platform and in line with the original direction of motion (Fig. 2). Approach speeds were monitored by a stopwatch over a 3-m distance and were required to fall between 4.5 and 5.5 m·s\(^{-1}\). This information was used to provide verbal feedback to the subjects and to ensure that we collected 10 trials where approach speed was within the specified range. A more accurate speed measurement was obtained afterwards for each trial, using the Motion Analysis System as described below. Cutting angles were required to be 30–40° from the original movement direction, in accordance with values typically observed in the game situation and adopted previously (19). Each angle was measured from the center of the force plate and the corresponding line was marked (using tape) so that it could be clearly seen by the subjects. A trial was deemed successful if the initial foot contact after the cutting action fell within this prescribed range. Subjects were required to continue running after sidestep execution for approximately five steps.

From the standing trial, a kinematic model comprised of five skeletal segments (foot, talus, shank, and thigh of the support limb, and the pelvis) and 14 degrees of freedom was defined using Mocap Solver 6.14 (Motion Analysis Corp.). Mocap Solver performs model-based kinematic analysis through global least-squares optimization (15).

In the kinematic model (Fig. 3), the pelvis was assigned six degrees of freedom relative to the global coordinate system. The hip joint possessed three degrees of freedom, with rotations (flexion-extension, abduction-adduction and internal-external rotation) defined about the three axes of a standard joint coordinate system (JCS; 29), passing through a fixed joint center defined according to Bell et al. (2). Knee joint rotations (flexion-extension, abduction-adduction, and internal external rotation) were also described about three JCS axes (11) passing through a fixed center defined according to Vaughan et al. (26). The ankle was modeled with two degrees of freedom, with plantar-dorsiflexion and pronation-supination occurring about a talocrural and subtalar joint axis, respectively (25). The talocrural joint center was defined as the midpoint between the lateral and medial malleoli, with the plantar-dorsiflexion axis originating and extending laterally from this point. The subtalar joint axis was located 10 mm directly below that of the talocrural joint (25), and oriented 42° from horizontal and 23° from the midline of the foot (13).

The 3D marker trajectories recorded during the sidestepping trials were processed by the Mocap Solver software to solve the generalized coordinates for each frame, that is, the...
14 degrees of freedom of the skeletal model. Joint rotations in hip, knee, and ankle were expressed relative to a neutral position where all segment axes are aligned (29). These data were low-pass filtered with a cubic smoothing spline at a 30-Hz cut-off frequency (28). Synchronized 3D ground reaction force (GRF) data were collected during each sidestep trial at 1000 Hz via the AMTI forceplate. These data were normalized to each subject’s body weight for statistical comparisons. Joint rotation and ground reaction force data for each trial were time-normalized to 100% of stance and resampled through linear interpolation at 1% time increments (N = 101), with heel strike defined as the instant when the vertical GRF first exceeded 10 N.

Intertrial variability demonstrated in kinematic and kinetic parameters across D and ND conditions was quantified for each subject. For each of the two defensive conditions, the standard deviation was computed for the ten trials at each time-step (N = 101) during stance. A mean SD was then obtained by averaging over all time steps. Similar measures of intertrial variability demonstrated during sidestepping have been adopted previously (19).

For each sidestepping trial, the velocity of the X coordinate (direction of motion) of the greater trochanter marker was calculated over the 10 video frames recorded before foot contact. Individual trial velocity data were subsequently submitted to a three-way ANOVA to verify that approach velocity was not influenced by defense condition, gender, or trial (random factor).

Eight variables were chosen for planned statistical comparisons, based on previous literature linked to ACL injury and the associated joint biomechanics. These were the peak (deviation from neutral) stance-phase values, extracted from each trial, for the following variables: medial GRF (MedGRF), hip flexion (HipFlex), hip abduction (HipAbd) hip internal rotation (HipInt), knee flexion (KneeFlex), knee valgus (KneeValg), knee internal rotation (KneeInt), and rearfoot pronation (AnklePron). Individual trial data were submitted to a two-way ANOVA to test for the main effects of gender and defense conditions. Subject was not included as a factor because it was found that the variability within subject was much larger than variability between subjects. The mean standard deviations were also extracted for the same eight variables and individual subject data were submitted to a two-way ANOVA to test for the main effects of gender and defense. A Bonferroni correction was applied to all analyses. An original alpha level of 0.05 was divided by 16 (8 peaks and 8 standard deviations), resulting in an alpha level of 0.003 being required for statistical significance.

RESULTS

Trial was not observed to have a statistically significant main or interactive effect on approach velocity comparisons. Thus, the statistical power of gender and defense condition comparisons was increased. Approach speeds were found to be similar between male (4.94 ± 0.24 m·s⁻¹) and female (4.92 ± 0.23 m·s⁻¹) (P = 0.864, observed power = 0.944) or between D (4.95 ± 0.19 m·s⁻¹) and ND (4.91 ± 0.26 m·s⁻¹) (P = 0.675, observed power = 0.902) conditions. This result implies that the remaining statistical comparisons to determine for the main effects of gender and defense condition were not influenced by differences in approach speed.

Group mean GRF and joint rotation data are presented as a function of stance time for both gender and defense (D and ND) conditions (Fig. 4). Females displayed larger peak knee valgus and rearfoot pronation angles, and smaller peak hip flexion, hip abduction, hip internal rotation, and knee flexion and internal rotation angles compared with males (P < 0.003; Table 2). Peak medial GRF data were similar between genders, after normalization to body weight (P = 0.79).

The simulated defensive opponent resulted in increases in peak medial GRF, hip flexion, hip abduction, knee flexion, and knee valgus (P < 0.003; Table 2). There were no statistically significant interactions between the effects of gender and defensive opponent.

Gender differences in mean intertrial variability measures were observed in hip joint internal-external rotation, knee joint varus-valgus, and knee internal-external rotation data (P < 0.003; Table 3). Significantly, males had more variability in hip rotation during the stance phase of the sidestep, whereas significantly greater variability was observed for females in both knee rotations. The simulated defensive opponent did not have an effect on the between-trial variability in any GRF or joint rotation variable.

DISCUSSION

The link between sidestepping and noncontact ACL injuries has been studied in research focusing primarily on knee joint loading, motion, and muscle action during these movements (5,7,17,19). However, recent research suggests that the biomechanical interaction of the entire lower extremity may be an important contributor to the overall risk of noncontact ACL injury (12,31). A combined analysis of all lower limb joint motions during sidestepping was therefore performed. Significant gender differences were found in all joints. Furthermore, the effect of a simulated defensive opponent on peak forces and joint angles was often as large as the effect of gender.

Mean knee joint flexion/extension data were similar to those reported previously for sidestepping, both in terms of movement patterns and associated peak flexion angles (17,19,22). The varus-valgus motions observed in the current study showed an oscillatory pattern, at a frequency of about 15 Hz, in early stance that was not reported previously (17,19). The valgus peak coincides with the impact peak in ground reaction force (Fig. 4A), which suggests an impact-related mediolateral oscillation in the lower extremity. The lower cut-off frequencies (8–14.9 Hz) used in previous studies (17,19) may have caused these rapid varus-valgus motions not to be seen. Peak knee internal rotation was larger than in previous studies (19) but well within passive rotation limits (external rotation = 45°, internal rotation = 25°) reported previously for the knee joint (30). Differences
in approach speeds (19) and cutting angle (17) may have contributed to this difference. The varus-valgus and internal-external rotation angles are small, which makes these variables sensitive to skin marker artifacts and the JCS definitions (23,24). This will be discussed in more detail when the limitations of the methodology are addressed.

FIGURE 4—Mean stance phase GRF and joint rotations demonstrated during sidestepping averaged for male (N = 8) and female (N = 8) subjects, and averaged for all subjects (N = 16) with (D) and without (ND) a simulated defensive opponent. Data are presented for: A, medial-lateral GRF; B, hip flexion-extension; C, hip abduction-adduction; D, knee flexion-extension; E, knee varus-valgus; F, knee internal-external rotation; and G, ankle eversion-inversion.
Hip rotation data from the current study, both in terms of the movement patterns and peak stance phase rotations, were similar to results of an earlier study on male subjects (22). After initial contact, hip flexion occurs due to the forward and downward movement of the trunk. The hip then extends through to toe off as the cutting phase of the movement is initiated and subsequently executed. Hip abduction and external rotation occur throughout stance, as the cutting maneuver is executed such that the resultant movement direction is opposite to the plant leg (see Fig. 4). Ankle plantar-dorsiflexion data were similar to those reported previously (22). Similarities were also evident in our male peak rearfoot supination-pronation data compared with that of Neptune et al. (22).

A statistical interaction between the effects of gender and defense condition on lower limb biomechanics during sidestepping was not found in the current study. Hence, gender-based differences in these variables occurred independent of the defensive condition employed, and further, the impact of the defensive condition was found to be similar across genders. The effects of these two factors will therefore be discussed separately.

The current study appears to present the most detailed comparison to date of male and female lower limb joint biomechanics associated with sidestepping. Significant gender effects were found in several key variables. Specifically, females exhibited increased peak knee valgus and rearfoot pronation angles, and decreased peak hip flexion, hip abduction, hip internal rotation, knee flexion, and knee internal rotation during sidestepping compared with the males. Increased peak knee flexion has been reported in females for sidestepping by Malinzak et al. (17) and has been interpreted as a risk factor for ACL injury because it increases the anterior drawer action of the quadriceps, as well as reduces the ability of the hamstrings to protect the ACL (7,17). Fagenbaum and Darling (8), however, reported that females landed with increased knee flexion compared with males during jump landing tasks and concluded that knee flexion angles would not contribute to the gender disparity in ACL injury risk. We have previously reported that males and females displayed similar knee flexion angles during sidestep cutting (19). It appears, therefore, that these results are sensitive to differences in the movement task and subject population. Reduced knee flexion observed in women may be a consequence of lower muscle strength. Further research is therefore required to identify whether there is in fact a consistent gender-based difference in knee flexion angles during sidestepping, and if so, determine whether peak knee flexion correlates prospectively with ACL injury risk. The gender effect on peak hip flexion was similar to that on knee flexion, suggesting that these variables are coupled to ensure that the body center of mass remains above the foot during stance.

Females had less internal tibial rotation during sidestepping than males. Similar trends were reported previously for gender comparisons during sidestepping (19). This result is to some extent counterintuitive, considering that females have an increased incidence of ACL injuries, and internal tibial rotation is known to be a contributor to ACL loading (14,18). This observation suggests, therefore, that the increased valgus found in females during sidestepping is the dominant risk factor for ACL injury. Increased knee valgus in females has been reported previously (18,20). Knee valgus is known to increase ACL loading (14,18) and is viewed as a key mechanism of noncontact ACL injury (3,20). The increased knee valgus demonstrated by women compared with men during sidestepping has been proposed previously to stem from gender-based anatomical differences, such as Q angle (19). We have recently shown that knee valgus loading during sidestepping is sensitive to neuromuscular control (20), and this is confirmed by the present study where substantial changes in peak valgus were seen between trials and defense conditions. If neuromuscular control, rather than anatomy, is largely responsible for knee valgus, prevention of ACL injuries in women may be possible. The gender difference of only two degrees (Table 2) in peak valgus may appear small and potentially unimportant in terms of injury potential, but a simple calculation will show that this can lead to 40 N-m change in valgus moment, assuming a GRF of 2500 N. This represents an increase of 100% relative to valgus loads reported previously (~40 N-m) during sidestep stance (3), making the limb more sensitive to valgus buckling. Gender comparisons of external joint loading demonstrated during sidestepping should therefore, be a useful extension of the current work.

It is increasingly recognized that abnormal knee joint loading may be a consequence of abnormal neuromuscular control of transverse and frontal plane rotations at the hip and/or ankle (12,31). No studies, however, have looked at

**TABLE 2.** Effect of gender and defense conditions on peak stance phase ground reaction force (GRF) and lower limb joint rotation variables demonstrated during sidestepping (mean ± SD).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Gender</th>
<th>Defense Condition</th>
<th>D</th>
<th>ND</th>
</tr>
</thead>
<tbody>
<tr>
<td>MedGRF (N·m)†</td>
<td>56.3 ± 13.2</td>
<td>47.4 ± 16.1</td>
<td>55.1 ± 15.6</td>
<td>48.6 ± 14.2</td>
</tr>
<tr>
<td>SDMedGRF (N·m)</td>
<td>5.0 ± 1.9</td>
<td>4.0 ± 1.2</td>
<td>4.2 ± 1.4</td>
<td>4.8 ± 1.8</td>
</tr>
<tr>
<td>SDHipFlex (°)</td>
<td>3.5 ± 1.3</td>
<td>3.5 ± 1.6</td>
<td>3.4 ± 1.4</td>
<td>3.5 ± 1.5</td>
</tr>
<tr>
<td>SDHipValg (°)</td>
<td>4.8 ± 1.6</td>
<td>2.8 ± 0.8</td>
<td>3.9 ± 1.9</td>
<td>3.7 ± 1.5</td>
</tr>
<tr>
<td>SDKneeFlex (°)</td>
<td>4.3 ± 0.9</td>
<td>3.8 ± 1.3</td>
<td>3.9 ± 1.0</td>
<td>4.2 ± 1.2</td>
</tr>
<tr>
<td>SDKneeValg (°)</td>
<td>1.9 ± 0.5</td>
<td>3.4 ± 0.9</td>
<td>2.6 ± 0.9</td>
<td>2.7 ± 1.3</td>
</tr>
<tr>
<td>SDKneeInt (°)</td>
<td>2.8 ± 0.9</td>
<td>4.8 ± 1.6</td>
<td>3.8 ± 1.3</td>
<td>3.9 ± 2.0</td>
</tr>
<tr>
<td>SDAnklePron (°)</td>
<td>3.4 ± 0.8</td>
<td>2.7 ± 0.9</td>
<td>3.1 ± 1.0</td>
<td>3.0 ± 0.8</td>
</tr>
</tbody>
</table>

* Denotes statistically significant difference between genders (P < 0.003).
+ Denotes statistically significant difference between defense conditions (P < 0.003).
D, simulated defense; ND, no defense.

**TABLE 3.** Effect of gender and defense conditions on mean intertrial SD calculated over the stance phase of sidestepping for GRF and lower limb joint rotation measures (mean ± SD).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Gender</th>
<th>Defense Condition</th>
<th>D</th>
<th>ND</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDMedGRF (N·m)</td>
<td>11.0 ± 1.1</td>
<td>11.0 ± 2.5</td>
<td>12.0 ± 1.9</td>
<td>10.0 ± 1.5</td>
</tr>
<tr>
<td>SDHipFlex (°)</td>
<td>54.1 ± 11.0</td>
<td>43.2 ± 7.5</td>
<td>51.9 ± 11.2</td>
<td>45.4 ± 9.5</td>
</tr>
<tr>
<td>SDHipAbd (°)</td>
<td>33.1 ± 8.9</td>
<td>26.7 ± 5.5</td>
<td>32.9 ± 8.6</td>
<td>26.9 ± 6.3</td>
</tr>
<tr>
<td>SDHipInt (°)</td>
<td>14.6 ± 7.8</td>
<td>8.4 ± 7.4</td>
<td>11.9 ± 8.8</td>
<td>11.1 ± 7.5</td>
</tr>
<tr>
<td>SDKneeFlex (°)</td>
<td>63.1 ± 9.5</td>
<td>57.2 ± 7.7</td>
<td>63.2 ± 8.8</td>
<td>57.1 ± 8.3</td>
</tr>
<tr>
<td>SDKneeValg (°)</td>
<td>12.1 ± 4.5</td>
<td>14.2 ± 5.2</td>
<td>15.0 ± 5.1</td>
<td>11.3 ± 4.1</td>
</tr>
<tr>
<td>SDKneeInt (°)*</td>
<td>19.2 ± 5.9</td>
<td>14.3 ± 5.4</td>
<td>16.9 ± 6.3</td>
<td>16.6 ± 6.1</td>
</tr>
<tr>
<td>SDAnklePron (°)*</td>
<td>1.5 ± 4.9</td>
<td>7.1 ± 6.8</td>
<td>4.4 ± 6.9</td>
<td>4.2 ± 6.9</td>
</tr>
</tbody>
</table>

* Denotes statistically significant difference between genders (P < 0.003).
+ Denotes statistically significant difference between defense conditions (P < 0.003).
D, simulated defense; ND, no defense.
gender differences in hip and ankle kinematics in sport movements commonly linked to ACL injury. We found that females had decreased hip abduction and internal rotation and increased rearfoot pronation during the stance phase of the sidestep compared with males. The decreased hip internal rotation observed in females during sidestepping, in conjunction with their demonstration of decreased knee internal rotation, supports previous theories that females tend to land in a more externally rotated position (12). The fact that we see synchronous impact peaks in external hip rotation and knee valgus (Fig. 4, D and F) suggests a causal link between these variables. Mechanically, valgus stress and rearfoot pronation may both be consequences of performing a deceleration task with an externally rotated lower extremity. At this time, it remains unclear whether increased external rotation of the lower limb during sidestepping is in fact a modifiable injury mechanism in females, or a necessary movement adaptation due to anatomical differences such as shorter bone lengths. The potential interaction between gender-specific anatomies, resultant lower limb neuromuscular control and the subsequent risk of noncontact ACL injury is extremely complex and is, hence, beyond the scope of the current investigation. Further studies, using forward dynamics techniques (20), are needed to study the causal relationships between these variables.

Although gender differences for other joint rotations primarily involved a shift or an amplification of a similar movement pattern (Fig. 4), unique ankle pronation patterns were seen for males and females during sidestepping. The current data suggest that males steadily supinate during the contact phase of the sidestep, indicating that the foot remains stationary while the upper body moves medially. Females show a damped oscillation toward a slightly pronated position and do not supinate at all until very late in stance. Individual differences in foot morphology are common and hence a great deal of variability exists in the segment’s true 3D rotational axes (13,25). In the current study, the talocrural axis was defined in accordance with mean population data presented previously (13). Hence, for the population tested, it is possible that individual differences in the true orientation of this axis impacted pronation/supination calculations. This variability needs to be considered in light of the current results. A relationship between rearfoot pronation and knee injuries in women has been proposed previously (12), and our results indicate that rearfoot pronation should be included as a variable in future prospective studies on risk factors for ACL injury.

Females demonstrated larger variability in varus-valgus and internal-external rotations at the knee. Increased variability in axial rotation data has been observed previously in sidestepping for females (19). However, this appears to be the first time that similar variability increases have been observed for knee varus-valgus rotations. Proposed reasons for increased knee rotation variability during complex movement patterns such as sidestepping include experience level (19), strength and conditioning, and neuromuscular control (31). More variable knee rotation patterns during sidestepping may increase the probability of performing an “abnormal” sidestepping maneuver that may result in increased knee joint and resultant ACL loading. Similarly, however, it is possible that increased variability in these movements may represent an ability to adapt more readily to changes in the movement environment, thus reducing injury potential. Further research into the relationship between knee joint variability during sidestepping and ACL injury risk is required. Females demonstrated lower variability in hip internal rotation than males. It is possible that in women, knee valgus is more sensitive to neuromuscular control at the hip because of differences in limb alignment and joint laxity. Women would therefore have to control their hip rotation more tightly in order to avoid excessive valgus stresses at the knee. Again, further work appears necessary to determine whether the current observation is consistent across other equally complex movement patterns, and if so, how this impacts knee joint and ACL loading.

Before the current study, kinematic data of the entire lower limb had not been compared between genders during sidestepping. Considering recent theories on the interaction between neuromuscular control of the entire lower limb and gender differences in knee injury (12,31), the outcomes of the current study are important. A number of differences between males and females existed in lower limb sidestep-kinematics that may provide insight into the gender-disparity in ACL injury rates. In particular, the increases in stance-phase valgus angles observed for females compared with males are relevant to the mechanism of noncontact ACL injury. Considering that similar results have been found previously for sidestepping (19) and that excessive valgus loading during sidestepping is increasingly thought to have a direct impact on injury potential (3,12), this postulate appears substantiated. Gender-based differences in both hip and ankle rotations were evident during the stance phase of the sidestep, which may have contributed to these increases in knee valgus. We propose the following mechanism: increased hip external rotation in females will cause increased valgus and pronation. With increased external rotation of the limb, valgus load becomes more sensitive to the amount of hip rotation and women compensate for this by controlling their hip rotation more tightly. When this control diminishes, due to fatigue or an unexpected perturbation, valgus may rise to a level where ACL injury occurs. Forward dynamics studies (20) are needed to confirm the existence of this injury mechanism. It is not clear why women would impact the ground with a more externally rotated limb. It may well be possible to reduce the risk of ACL injuries through neuromuscular training to specifically avoid these postures. We wish to emphasize that there was considerable variation between subjects within each gender (Tables 2 and 3), which indicates that other results may be obtained in other subject populations. The present study population consisted of active men and women, but these were not competitive athletes.

Factors other than gender may influence lower extremity kinematics in a way that impacts the risk of ACL injury, and it is especially important to know if these effects may be gender-dependent. When a defensive opponent is present,
subjects may perceive a need to change direction more rapidly during the plant and cut phase of the movement. This would explain our finding of a larger medial ground reaction force and larger hip abduction and knee valgus angles for the defensive condition. We also found larger hip and knee flexion angles, which may reflect a need for a more rapid deceleration on initial contact due to the imposed spatial changes, and a greater amount of muscle shortening to generate more energy in the take-off phase of the movement. Based on these findings, the presence of a defensive opponent increases the loading of the knee joint, possibly bringing the movement closer to an ACL injury scenario. Inclusion of a simulated defensive opponent is therefore a useful addition to the test protocol. The defensive opponent was not found to have no effect on between-trial variability, which is consistent with the finding that visual targeting during walking has no effect on the variability of ground reaction force data (27). A limitation of our study was that a static obstacle was used to simulate the defensive opponent. Considering the potential importance of this factor, further studies may be needed to assess the influence of obstacles with unpredictable active behavior. It has been shown that decision-making has the potential to influence neuromuscular control (5).

As is the case with all assessments of in vivo joint motion, the accuracy of results is limited by the use of skin markers. The impact of skin marker movement error is unknown for sidestepping movements, but we have taken several steps to minimize this problem and estimate its influence. First, we adopted a model-based global optimization technique (15), which makes use of the fact that, on the scale of gross movement, joints have fewer than six degrees of freedom. It has been shown that this assumption makes results less sensitive to errors in marker trajectories (15), because redundancy in the marker set is better exploited. A further advantage of this technique is that fewer than three markers per body segment can often be used. This allowed us to perform the analysis without a third (frontal) marker on the thigh, which we found to be the main source of skin motion artifacts in knee joint rotations. The Mocap Solver software allowed us to perform the global optimization with various models and marker sets to solve skeleton motion. We always found joint motion patterns that were consistent with those obtained from the full model and marker set. For instance, the oscillatory features in valgus and hip rotation were always there, and with amplitudes that were too large to be explained by skin motion artifact. Based on these methodological improvements, a 30-Hz cut-off frequency was chosen to filter the data. It is possible that filtering data at this frequency may have failed to remove some movement artifacts due to skin marker movement on impact. As noted above however, adopting previously used frequencies (8–14.9 Hz) may in fact filter out real motion synonymous with sidestepping. Further, if the oscillatory peaks in valgus data (~6°) were based purely on skin motion artifact, marker movement of approximately 40 mm would be required, which far exceeds ranges proposed possible for skin marker error during gait (6) and appears unlikely with our marker set (Fig. 1). Finally, even though skin marker artifacts may have influenced the patterns of joint motion, the same effects would have been detected by the statistical analysis if we assume that relative movement between skin and bone is not affected by gender or defensive condition.

Another known problem in knee joint kinematics is the fact that valgus and internal rotation are small relative to the flexion-extension motion, and therefore easily influenced by minor variations in the definition of the JCS (23,24). This “kinematic crosstalk” problem may explain why two previous studies (17,19) found opposite varus-valgus angles, and why our internal rotation angles are higher than that observed in those studies. Our internal rotation angles are highly correlated to the flexion angles, which is consistent with a “screw home” mechanism. It has been suggested that this may merely be a manifestation of the fact that the first JCS axis, the femur-fixed flexion axis, is not parallel to the functional flexion axis (23). This should be kept in mind when interpreting the internal rotation results. For instance, the larger internal rotation in males is probably partly due to the larger flexion angle in males.

The current study presented a combined analysis of 3D hip, knee, and ankle motions during sidestepping, based on evolving theories that the biomechanical interaction of the entire lower extremity may be an important contributor to the overall risk of noncontact ACL injury. However, it failed to incorporate an analysis of upper-body (trunk) motion. Understanding the interaction between trunk motion and those of the lower limb joints during sidestepping may provide further insight into the resultant injury mechanism. For instance, trunk accelerations at contact will have a significant impact on the coupled hip and knee flexion, and more than likely, on out-of-plane loading at the knee joint. Future biomechanical research into sidestepping would benefit from the incorporation of such analyses.

**CONCLUSIONS**

Based on the research outcomes obtained for the population tested, the following conclusions can be drawn:

1. Women execute sidestepping movements with less hip flexion, abduction and internal rotation and knee flexion and internal rotation, and greater knee valgus and rearfoot pronation compared with men.
2. Movement variability was greater for women in the transverse and frontal plane rotations at the knee but less in frontal plane hip rotations.
3. Increased knee valgus appears to be a risk factor for ACL injury that is related to increased hip external rotation and rearfoot pronation. These variables would be good candidates for inclusion in prospective studies or as target variables in neuromuscular training programs.
4. The presence of a defensive opponent appears to result in sidestepping movements characterized by increased deceleration of the body segments upon contact, causing a concomitant increase in knee joint rotations of similar magnitude as the effect of gender. Hence, its inclusion should be considered in future laboratory-based investigations into the...
link between sidestepping maneuvers and noncontact ACL injury.

REFERENCES


This research was funded by the National Institutes of Health (1R01-AR47039).