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Differences in Kinematics and Electromyographic Activity Between Men and Women during the Single-Legged Squat*

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Background: Numerous factors have been identified as potentially increasing the risk of anterior cruciate ligament injury in the female athlete. However, differences between the sexes in lower extremity coordination, particularly hip control, are only minimally understood.
Hypothesis: There is no difference in kinematic or electromyographic data during the single-legged squat between men and women.
Study Design: Descriptive comparison study.
Methods: We kinematically and electromyographically analyzed the single-legged squat in 18 intercollegiate athletes (9 male, 9 female). Subjects performed five single-legged squats on their dominant leg, lowering themselves as far as possible and then returning to a standing position without losing balance.
Results: Women demonstrated significantly more ankle dorsiflexion, ankle pronation, hip adduction, hip flexion, hip external rotation, and less trunk lateral flexion than men. These factors were associated with a decreased ability of the women to maintain a varus knee position during the squat as compared with the men. Analysis of all eight tested muscles demonstrated that women had greater muscle activation compared with men. When each muscle was analyzed separately, the rectus femoris muscle activation was found to be statistically greater in women in both the area under the linear envelope and maximal activation data.
Conclusions: Under a physiologic load in a position commonly assumed in sports, women tend to position their entire lower extremity and activate muscles in a manner that could increase strain on the anterior cruciate ligament.

Many investigations have demonstrated the difference in noncontact ACL injury incidence between men and women. There continues to be much debate about the cause of this difference. One of the major areas of interest is the role of dynamic neuromuscular control of the trunk, hip, and femur over the planted leg.[17] Biomechanical studies have demonstrated a major role of hip muscle activation in increasing quadriceps and hamstring muscle activation during running and jumping, allowing increased control over forces in the entire leg.[7,35]

There has been little research, however, on the role of the hip as a potential risk factor in noncontact ACL injuries, although it has been mentioned in studies of potential methods to prevent ACL injuries.[23,24] In 2000, Griffin et al.,[17] in reporting the results of a consensus conference, stated that "the knee is only one part of a kinetic chain; therefore, it must be borne in mind that anatomic sites other than the knee, including the trunk, hip and ankle, may have a role in ACL injury." The authors concluded that strengthening programs that emphasize proper hip control and strength are beneficial in injury prevention, yet published research involving the hip as a risk factor in ACL injury is limited.

One of the standard tests in the preparticipation phys-

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ical examinations conducted at the Lexington Sports Medicine Center is the single-legged squat. The test simulates a common athletic position, requires control of the body over a planted leg, and is used to screen for poor hip strength and trunk control. We had anecdotally noted a general tendency for female subjects to have decreased hip control when going down and coming up in the squat. The purpose of this study was to observe the differences in the squat between men and women and to evaluate the data in reference to possible risk factors for noncontact ACL injury. We kinematically and electromyographically analyzed the performance of single-legged squats by male and female intercollegiate athletes. This research was designed as an initial investigation into the hip and thigh musculature. The null hypothesis for this study, which was formulated before data collection, was that there are no differences in any kinematic or EMG data between healthy male and female subjects.

MATERIALS AND METHODS

Subjects

Eighteen healthy, intercollegiate athletes (9 men, 9 women) from a local National Association of Intercollegiate Athletics institution were recruited to participate in this study. Demographic data for all subjects are shown in Table 1. To be included in the study, subjects had to have been a member of a varsity intercollegiate team within the past year and have no history of major hip or knee injuries or surgery on either lower extremity. Examples of injuries that excluded participation were grade 2 or greater ligament injury, meniscal tears, severe chondromalacia, osteochondritis dissecans, patellar dislocations, or any fracture of the lower extremity. Subjects with a history of minor strains, sprains, or chronic conditions such as tendinitis or bursitis in the dominant extremity that had completely healed or were causing no pain at the time could be included in the study. The dominant leg was determined by having each subject select the leg for use when kicking a soccer ball.[33] Before participating, subjects were informed of possible risks and signed a consent form approved by the University of Kentucky Medical Institutional Review Board.

Instrumentation

Six high-speed Falcon high-resolution video cameras (Motion Analysis Corp., Santa Rosa, California) were positioned at various locations in the University of Kentucky Biodynamics laboratory to sample kinematic data at 60 Hz. The cameras were positioned to allow each of the retroreflective markers placed on the subjects to be seen by at least two cameras in each frame. All video and analog data were collected by using the EVa HiRES 6.0 hardware-software system (Motion Analysis Corp.) and stored on a personal computer. Video data were tracked and smoothed using a Butterworth fourth order low-pass filter with a cutoff frequency of 6 Hz in the EVa 6.0 software and then were exported to the OrthoTrak 4.2 software (Motion Analysis Corp.) for analysis. Three-dimensional joint angles for the trunk, hip, knee, and ankle were determined.

Surface electrodes (silver-silver chloride) with on-site preamplifiers (Model D-100, Therapeutics Unlimited, Iowa City, Iowa) were used to access EMG activity of the following eight muscles of the dominant extremity of each subject: rectus femoris, vastus lateralis, medial gastrocnemius, biceps femoris, gluteus maximus, gluteus medius, rectus abdominis, and erector spinae. The electrode position for each muscle was located over the midsection of the muscle, as described by Cram et al.[11] Before the application of an electrode, the skin was prepared by dry-shaving the area and cleansing the skin with alcohol to reduce surface impedance. A prefabricated piece of double-sided adhesive tape and conductive gel was then applied to each electrode, after which the electrode was applied to the midsection of the muscle belly. To ensure accurate electrode placement, we instructed the subject to contract each of the muscles being tested while an investigator observed the EMG signal on the oscilloscope. Electromyographic data were sampled at 960 Hz, amplified, and rectified with a low-pass filter at 15 Hz with a fourth order Butterworth filter. Electromyographic data were recorded synchronously with video data and stored on the same personal computer. The EMG data were analyzed with a customized Matlab program (The Mathworks, Inc., Natick, Massachusetts). Data were normalized to the percentage of maximal voluntary isometric contraction to allow for comparison between subjects.

TABLE 1
Demographic Data (Mean ± SD) on the 18 Subjects Undergoing Kinematic and EMG Testing

Variable	Men	Women
Age (years)	20.33 ± 1	20.00 ± 1.50
Height (inches)	72.44 ± 2.01	67.44 ± 2.40
Weight (pounds)	173.89 ± 8.94	141.89 ± 12.33
Sports	Soccer, $N = 3$	Volleyball, $N = 7$
	Basketball, $N = 3$	Softball, $N = 2$
	Baseball, $N = 3$	

Protocol

On arrival at the Biodynamics laboratory, subjects underwent placement of the surface EMG electrodes over the eight muscles as discussed earlier. Each subject was then asked to perform two maximal voluntary isometric contractions, holding each for 3 seconds. Subjects were positioned and pressure was directed as described by Kendall et al.[25] for all maximal voluntary isometric contractions.

After muscle contraction data were collected, the kinematic reflective markers were placed on the subject by using a standard Cleveland Clinic marker setup (Fig. 1). After collection of an anatomic calibration file, which determined the location of joint centers, subjects were instructed and given an opportunity to practice the single-legged squat maneuver. Subjects were instructed to stand

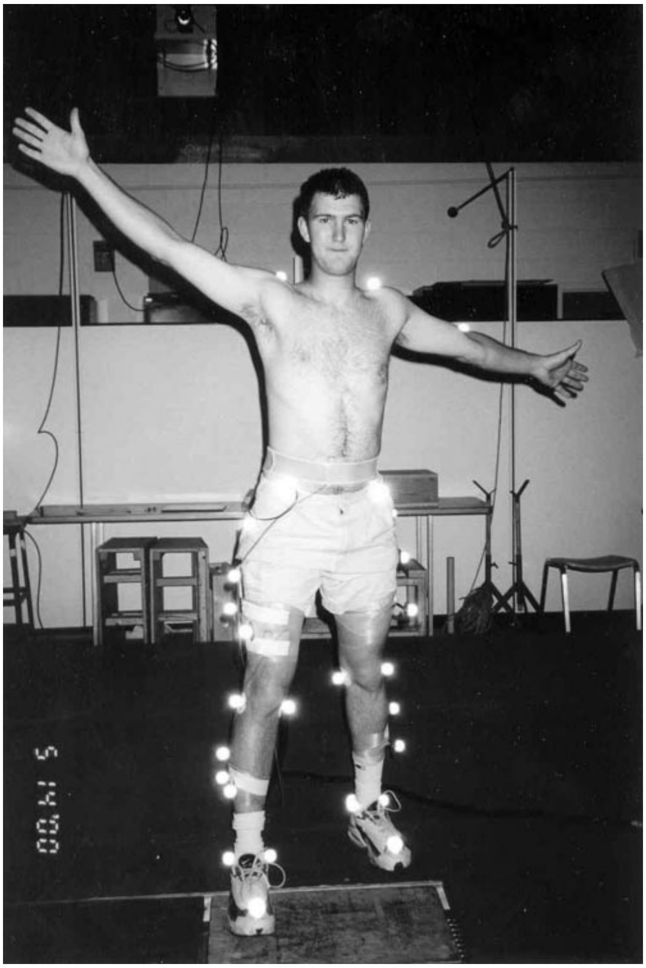

Figure 1. Kinematic marker placement–Cleveland Clinic marker setup.

on their dominant extremity, cross their arms over their chest, squat down as far as possible, and then return to a single-legged stand without losing their balance, all within a 5-second period. Once each subject felt comfortable with the maneuver, he or she performed five single-legged squats.

Statistical Analysis

One-way analysis of variance tests were used to analyze the difference between male and female subjects in all kinematically observed ranges of motion. The EMG data were analyzed with a Matlab program, looking at the area under the linear envelope and the maximum activation for each muscle. Mean EMG data for the nine male and nine female subjects were analyzed for differences between the two groups by using a multivariate analysis of variance and then by using a one-way analysis of variance for results for each individual muscle. The level of significance was set at $P < 0.05$.

RESULTS

Kinematic Results

Using all of the data points in a one-way analysis of variance, we found significant differences between men and women in several joint motions ($P < 0.05$). Women demonstrated significantly more ankle dorsiflexion, ankle pronation, hip adduction, hip flexion, and hip external rotation. They also demonstrated less trunk lateral flexion than the men. Women also started in a more valgus position, relative to the men, and remained in a more valgus alignment throughout the squat. Table 2 summarizes the maximum range of motion achieved for male and female subjects for each range of motion and the levels of significance. These data show that in an uninjured, athletic population, there are definitive sex-related differences in how men and women perform a single-legged squat. These differences are noticeable in the frontal planes of ankle pronation/supination range of motion (Fig. 2), knee valgus/varus (Fig. 3), and hip adduction/abduction (Fig. 4).

EMG Results

The multivariate analysis of variance of EMG data for all of the muscles analyzed together showed that women had a greater activation measured by the area under the linear envelope compared with the men ($P < 0.05$). When each muscle was analyzed separately, the rectus femoris muscle was found to have statistically greater activation in women ($P < 0.05$) in both the area under the linear envelope and the maximum activation data. Tables 3 and 4 show the mean EMG values and standard deviations for each muscle, along with their level of significance for the area under the linear envelope and maximum activation data.

TABLE 2
Mean Maximum Range of Motion in All Directions for Men and Women Performing a Single-Legged Squat

Motion	Range of motion (deg)		P value[a]
	Men	Women	
	Mean ± SD	Mean ± SD	
Ankle			
Dorsiflexion	34.8 ± 5.3	41.5 ± 4.0	0.003[b]
Supination	1.0 ± 1.3	0.7 ± 1.2	0.000[b]
Pronation	5.2 ± 4.2	7.9 ± 6.3	0.000[b]
Knee			
Flexion	89.5 ± 6.2	95.4 ± 6.2	0.292
Varus	14.4 ± 13.1	6.4 ± 8.5	0.000[b]
Valgus	5.1 ± 4.9	7.0 ± 7.0	0.000[b]
Hip			
Flexion	60.0 ± 8.1	69.1 ± 8.4	0.032[b]
Extension	12.5 ± 5.6	8.5 ± 5.7	0.032[b]
Adduction	14.6 ± 5.4	17.8 ± 6.3	0.000[b]
External rotation	4.6 ± 15.5	11.2 ± 10.2	0.000[b]
Trunk			
Flexion	30.5 ± 13.7	29.5 ± 10.1	0.299
Lateral flexion	26.4 ± 20.1	9.8 ± 9.1	0.000[b]

[a] P values represent differences in each plane of movement between men and women.
[b] Statistically significant ($P < 0.05$).

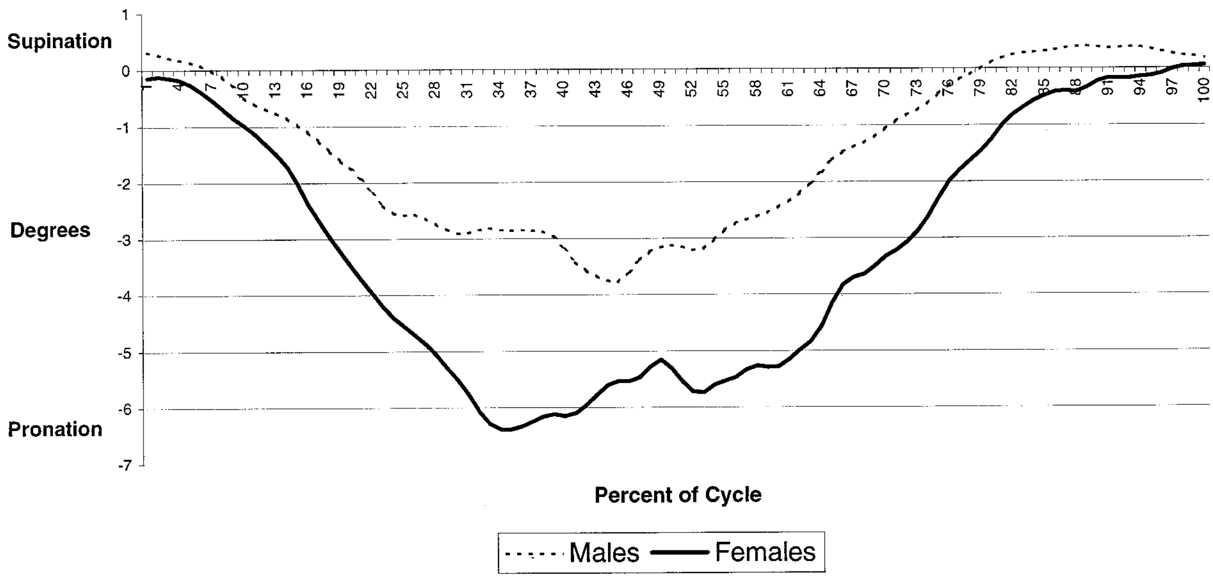

Figure 2. Mean ankle pronation/supination angle in the frontal plane for men and women during the single-legged squat. The beginning of the chart (0% of the cycle) and the end of the chart (100% of the cycle) represent the subject in a single-legged stand before initiating the movement and at the end of the squat. The middle portion of the chart represents the actual squat movement with the lowest point at approximately 50% of the cycle.

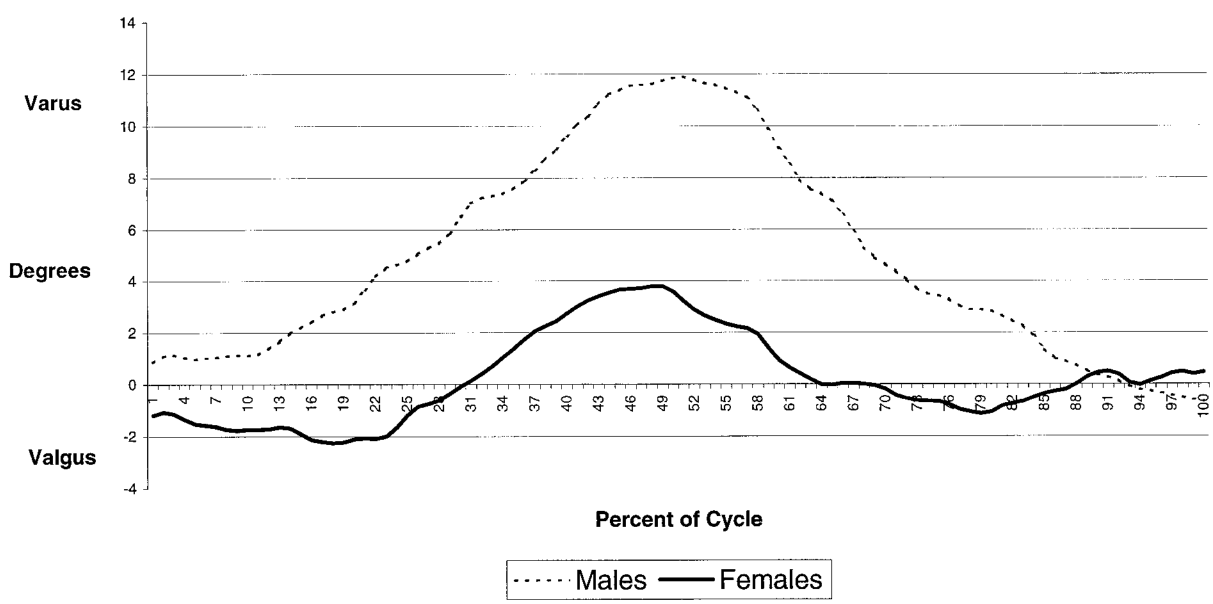

Figure 3. Mean knee varus/valgus angle in the frontal plane for men and women during the single-legged squat. See legend for Figure 2 for graph information.

DISCUSSION

Research studies focusing on noncontact ACL injuries have demonstrated that women have a two to eight times greater risk of an ACL injury than men.[2,6,13,14,16,22,23] Most of this research has focused on either extrinsic or intrinsic risk factors for the female athlete. Although this research has been extremely useful in identifying the majority of risk factors associated with ACL injury, it is possible that there are other factors that need to be addressed.

Numerous risk factors have been proposed and researched in an attempt to explain the reasons for such a difference in injury occurrences. Extrinsic factors are very difficult to measure in a sport-specific manner; however, these factors are considered potentially controllable or changeable in both the male and female athlete.[18] Intrin-

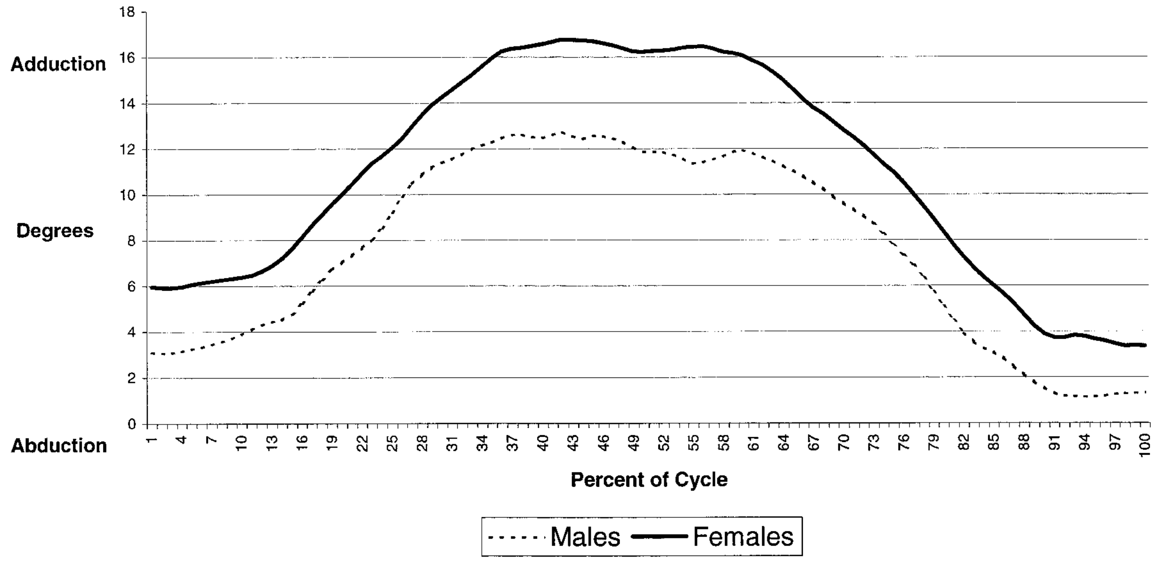

Figure 4. Mean hip adduction/abduction angle in the frontal plane for men and women during the single-legged squat. See legend for Figure 2 for graph information.

sic factors have been described by Arendt et al.[1] as those factors that are individual, physical, and psychosocial. Intrinsic factors have been found to be more sex-specific and less likely to be changeable.[18] The extrinsic category includes risk factors such as conditioning levels, body movement and positioning, decreased strength of the quadriceps and hamstring muscles, decreased neuromuscular coordination, and improper shoe wear or shoe-surface interface.[1–3,8,15,21–23,30,34] The intrinsic category includes factors such as increased joint laxity; limb alignment, which includes such factors as an increased Q angle, genu recurvatum, and excessive external tibial torsion; width and shape of the intercondylar notch; ligament size; hormone levels; and foot abnormalities.[1–3,8,9,12,15,19,21–23,32,34,37] Although all of these factors may have some direct or indirect effect on injury risk patterns in female athletes, none of them could be considered a primary cause above any other. In fact, the current thought is that increased ACL injury risk in the female athlete is more the result of a combination of factors, not the result of one factor alone.[1,18]

The purpose of this study was to determine whether there are kinematic and EMG differences between men and women in how the hip is controlled during a single-legged squat. A lack of control at the hip might place the ACL at an increased risk of injury. The results of this study demonstrate that uninjured female athletes have an increased amount of hip adduction when performing a single-legged squat as compared with male athletes. This could indicate that women may have difficulty controlling the hip musculature, especially the gluteus medius muscle, during a dynamic movement and that they rely more on the quadriceps muscles for control of the knee. When an athlete has poor hip control, especially in the gluteus medius muscle, the hip will tend to move into adduction when loaded.[36] Once the hip moves into adduction, the femur internally rotates[26] and the knee is placed into a valgus position. The combination of these events places the athlete into the "position of no return," as described by Ireland.[23] However, some of the differences between the sexes may by due to kinetic and anthropometric

TABLE 3
Mean Area under the Linear Envelope Data for Men and Women Performing a Single-Legged Squat[a]

Muscle	Men	Women	P value
	Mean ± SD	Mean ± SD	
Rectus femoris	34.4 ± 16.4	78.8 ± 26.1	0.000[b]
Vastus lateralis	89.4 ± 48.1	164.6 ± 100.1	0.059
Medial gastrocnemius	49.1 ± 61.5	117.1 ± 127.6	0.169
Biceps femoris	24.8 ± 18.9	143.0 ± 351.5	0.328
Gluteus maximus	74.5 ± 58.7	97.9 ± 38.2	0.331
Gluteus medius	78.5 ± 81.8	47.8 ± 22.4	0.294
Rectus abdominis	22.9 ± 41.0	8.5 ± 9.0	0.319
Erector spinae	39.8 ± 7.6	45.5 ± 29.8	0.584

[a] Values are percentage of maximal voluntary isometric contraction.
[b] Statistically significant ($P < 0.05$).

TABLE 4
Mean Maximum Activation EMG Data for Men and Women Performing a Single-Legged Squat[a]

Muscle	Men	Women	P value
	Mean ± SD	Mean ± SD	
Rectus femoris	36.2 ± 14.5	83.4 ± 14.5	0.015[b]
Vastus lateralis	81.4 ± 41.4	116.2 ± 73.5	0.234
Medial gastrocnemius	40.0 ± 26.2	109.4 ± 121.8	0.114
Biceps femoris	38.4 ± 33.1	24.5 ± 11.4	0.352
Gluteus maximus	62.7 ± 43.8	81.2 ± 28.9	0.199
Gluteus medius	77.3 ± 64.3	41.0 ± 29.5	0.143
Rectus abdominis	18.2 ± 36.0	110.4 ± 278.6	0.339
Erector spinae	41.6 ± 17.5	35.7 ± 19.2	0.505

[a] Values are percentage of maximal voluntary isometric contraction.
[b] Statistically significant ($P < 0.05$).

differences. These factors will be examined in a future study.

The frontal plane knee data revealed that, during performance of the single-legged squat, women, while still in the position of standing on a single leg, begin the squat with the knee in a slightly valgus position (±1°) (Fig. 3). This is most likely because women have the intrinsic biomechanical factor of a wider pelvis, which changes the angle of the femur with respect to the tibia. When the female athletes in this study began to move into a single-legged squat, the knee was moved slightly further into a valgus position (±2.5°) and then into varus positioning for the remainder of the descent and most of the ascent phases of the movement. Then, near the end of the ascent phase, the female athletes exhibited slightly less control when the knee reverted into a valgus position (±1°). In contrast, the men never moved their knee into a valgus position during the squat; instead, they moved the knee into a significantly varus position (±12°). It appears that women tend to lose control of the knee into a slight valgus position at the start of the movement; regain control, moving into a safe varus position; and then have a slight loss of control as the knee moves into a valgus position during the final ascent of the squat.

Ireland[23] has described a common mechanism by which noncontact ACL injuries occur in the female athlete. She termed this the position of no return and described it as a loss of control at the hip and pelvis, internal rotation of the femur, valgus knee angulation, and external tibial rotation on a pronated, externally rotated foot. Our data are in agreement with the position described by Ireland, with the exception that the female subjects in our study demonstrated increased external hip rotation. When our subjects performed the single-legged squat, we noted that the female subjects tended to rotate their pelvis away from the dominant leg to maintain their center of gravity. In other words, if a female subject stands on her right leg, the pelvis moves in a counterclockwise direction, such that the left anterior superior iliac spine of the subject moves from the 9-o'clock to 6-o'clock position if the pelvis were being observed from a superior view. This movement of pelvis rotation on a fixed femur (closed chain) may have been interpreted as the femur externally rotating at the pelvis (open chain). Ireland[23] also states that the actual rupture of the ACL most likely occurs very early, before the knee reaches the extreme valgus position often described in noncontact ACL injuries.

When performing the single-legged squat, the female athletes in this study tended to have an initial loss of control of the knee into a valgus position combined with greater hip adduction (Fig. 4) and foot pronation (Fig. 2). Although the single-legged squat evaluated in this study is a dynamic movement, it certainly does not place the concentric and eccentric loads on the knee that landing and deceleration moments would. However, the increased knee valgus position observed in our female study athletes makes it reasonable to assume that the landing or deceleration movement would be even less controlled.

A point must be addressed when considering the knee varus/valgus data (Fig. 3) in terms of combining the kinematic data and the EMG results we observed. As previously stated, the female subjects demonstrated a loss of dynamic control at the start and end of the squat. The EMG data revealed that the female subjects had greater rectus femoris muscle activation in both the area under the linear envelope and results of maximum activation. During the single-legged squat, the rectus femoris muscle would be acting eccentrically to control knee flexion during the descent phase and concentrically extending the knee in the ascent phase. This indicates that the women were attempting to use their quadriceps muscles to maintain the position of the knee in the frontal plane; however, even with this activation, the position of the knee in the frontal plane was not maintained. Therefore, the quadriceps muscles cannot be seen as the culprit in the lack of knee control in the female subjects in this study. Future research into the activation patterns of the hip musculature is necessary to determine whether the hip is initiating this movement of the knee into a valgus position.

A question to consider is whether the loss of hip control demonstrated by increased hip adduction, flexion, and external rotation is causally related to a loss of knee varus/valgus control. If the hip adducts, the femur generally internally rotates,[26] which results in the knee being forced into a degree of valgus. Recently, researchers have investigated risk factors involving the ankle and foot that may cause a predisposition for ACL injury.[4,38] Results have indicated that factors such as hyperpronation may increase the risk of injury, but the authors of these studies stopped short of suggesting that these were initiating factors. Although the current study does not answer the question of whether the hip is an initiator of ACL injury in the female athlete, it does show an association, consistent with other biomechanical data, of the coupled mechanical interrelationships of the hip and knee with muscle activation.[7,28,35]

When addressing the hip as a potential risk factor for ACL injury in the female athlete, one generally thinks first of the intrinsic, biomechanical alignment of the female lower extremity as compared with that of a male athlete. Huegel et al. (unpublished data, 1997), in studying the contribution of lower extremity biomechanical factors to noncontact ACL injuries, found no statistically significant difference between men and women in either femoral anteversion or Q angle. However, they did find a difference in the thigh/foot angle of the injured population, with the foot contacting the playing surface with a greater degree of external rotation than was seen in the uninjured group. In other studies, Loudon et al.[27] and Gray et al.[16] also found no correlation between an increased Q angle and ACL injury.

No static measurements of any lower extremity alignment were obtained during the present study because of the dynamic nature of the movement being studied. We were more concerned with the resultant position of a dynamic movement, and not the static, sedentary position. Current research being performed has added these measurements into the data analysis to determine whether there is a correlation between the static and dynamic positions. However, this study also shows that there are sex differences in dynamic ankle control. It is not clear whether these are feedback compensations to maintain balance in the face of increased knee and hip motion, or parts of a specific physiologic and biomechanical pattern adopted to provide trunk and leg stability, or are the underlying causative factors creating the altered motions at the other lower extremity joints. There is no consensus about these roles. In light of the data supporting the importance of the hip muscle activation in maximizing knee and ankle muscle activation,[7,35] the finding that dynamic ankle/foot pronation is created by proximal motion and position,[5] and that the interactive movements controlling distal body segments are generated by proximal segment activations,[28] we do not believe the ankle motion differences are the primary causative factors but, in fact, accompany the more proximal changes.

Sex differences in neuromuscular characteristics have been extensively studied.[20,21,30,31,33] Huston and Wojtys[21] found no significant differences in either spinal or cortical muscle reaction times in simulated anterior translation movements; however, female athletes appeared to rely more on their quadriceps muscles in response to anterior translation, whereas male athletes relied more on their hamstring muscles.[21] This initial increased use of the quadriceps muscles and decreased use of the hamstring muscles could place greater stress on the ACL in these female athletes, making it more susceptible to rupture. We also found that female athletes tend to activate their rectus femoris muscle to a greater degree than male athletes while performing a single-legged squat, which is a dynamic movement. This is of concern because of the known deleterious effects of extensive quadriceps muscle activation on ACL strain[21,29] and anterior translation of the tibia.[10] Griffin et al.[17] reiterated this in their consensus statement that "quadriceps activation during eccentric contraction was considered to be a major factor in injury to the ACL."

Neuromuscular coordination data more specific to the hip have shown that women exhibit a shorter duration of gluteus medius muscle activation while in the stance phase when performing a cutting maneuver (W. B. Kibler, unpublished data, 1999). Decreased muscle activation at the hip also decreases maximal quadriceps and hamstring muscle activation,[17] which limits the dynamic stability of the knee joint.

This study does have some limitations. First, the depth of the squat was not adequately controlled for each subject. Subjects were instructed to squat down on their dominant extremity as far as possible and return to a single-legged stand without losing their balance. It is possible to estimate the depth of the squat by looking at the amount of knee flexion and hip flexion for each subject (Table 2); however, precise data for individual squat depth was not obtained. This limitation is being addressed in a current study. Second, the number of total subjects was limited and may not be an adequate sample of the population. Current research will increase the number of both female and male subjects as well as collect data on multiple intrinsic and extrinsic factors.

CONCLUSIONS

This study demonstrated sex differences in the performance of a single-legged squat, a common athletic maneuver that is important in cutting, jumping, and balancing. Female athletes showed larger excursions in hip flexion, hip external rotation, hip adduction, knee varus/valgus position, ankle dorsiflexion, and ankle pronation. The combination of these kinematic differences at the hip suggests that the hip should be examined more closely as a risk factor for an ACL injury in the female athlete. Future research should be directed at potential anthropometric differences, strength differences, and neuromuscular characteristics at the hip and trunk in the female and male athletes. Studies focusing on potential training effects at the hip that reduce the risk of ACL injury and prospective kinematic studies will help to clarify the importance of the hip in the female athlete.

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