Relationship Between Hip and Knee Strength and Knee Valgus During a Single Leg Squat

Tina L. Claiborne1, Charles W. Armstrong2, Varsha Gandhi2, and Danny M. Pincivero2

1The University of Southern Maine; 2The University of Toledo

The purpose of this study was to determine the relationship between hip and knee strength, and valgus knee motion during a single leg squat. Thirty healthy adults (15 men, 15 women) stood on their preferred foot, squatted to approximately 60 deg of knee flexion, and returned to the standing position. Frontal plane knee motion was evaluated using 3-D motion analysis. During Session 2, isokinetic (60 deg/sec) concentric and eccentric hip (abduction/adduction, flexion/extension, and internal/external rotation) and knee (flexion/extension) strength was evaluated. The results demonstrated that hip abduction ($r^2 = 0.13$), knee flexion ($r^2 = 0.18$), and knee extension ($r^2 = 0.14$) peak torque were significant predictors of frontal plane knee motion. Significant negative correlations showed that individuals with greater hip abduction ($r = -0.37$), knee flexion ($r = -0.43$), and knee extension ($r = -0.37$) peak torque exhibited less motion toward the valgus direction. Men exhibited significantly greater absolute peak torque for all motions, excluding eccentric internal rotation. When normalized to body mass, men demonstrated significantly greater strength than women for concentric hip adduction and flexion, knee flexion and extension, and eccentric hip extension. The major findings demonstrate a significant role of hip muscle strength in the control of frontal plane knee motion.

Key Words: biomechanics, closed kinetic chain, gender, peak torque, isokinetic

As many knee injuries occur in noncontact situations (Boden, Dean, Feagin, & Garrett, 2000; Ferretti, Papandrea, Conte, & Marian, 1992), factors contributing to joint stability, such as muscle strength, may function as a protective mechanism. While muscular control of the knee in the sagittal plane has been well documented (Escamilla, 2001; Gryzlo, Patek, Pink, & Perry, 1994; Isear, Erickson, & Worrell, 1997), the relationship between varus/valgus control and lower extremity muscle strength during weight bearing activities remains equivocal. The control of frontal plane knee motion, particularly toward the valgus direction, is clinically important, as this movement places stress on passive tissue restraints and, in combination with anterior tibial translation, strain on the anterior cruciate ligament (ACL) is increased (Berns, Hull, & Patterson, 1992; Markolf, Burchfield, Shapiro, et al., 1995). As femoral adduction and internal rotation contribute to a knee valgus position, it may be surmised that muscular control of the hip joint may assist in frontal plane knee control (Norkin & Levangie, 1992; Zeller, McCrory, Kibler, & Uhl, 2003).

The influence of knee and hip muscle strength on lower extremity kinematics during weight bearing activities has significant implications for movement control, particularly as it relates to potential differences between men and women. As female athletes have demonstrated a higher incidence of ACL injuries than male athletes (Arendt & Dick, 1995; Gwinn, Wilckens, McDevitt, Ross, & Kao,
Claiborne, Armstrong, Gandhi, and Pincivero (2000), a contributory factor may be an increased valgus knee position during dynamic weight bearing activity in women (Chappell, Yu, Kirkendall, & Garrett, 2002; Ford, Myer, & Hewett, 2003; Malinzak, Cloby, Kirkendall, Yu, & Garrett, 2001; McLean, Neal, Myers, & Walters, 1999). Furthermore, when normalized to body mass, men have been shown to generate significantly greater knee extensor and flexor torque than women during maximal-effort contractions (Hakkinen, Kraemer, & Newton, 1997; Hewett, Stroupe, Nance, & Noyes, 1996; Huston & Wojtys, 1996; Kanehis, Okuyama, Ikegawa, & Fukunaga, 1996; Pincivero, Gandaio, & Ito, 2003). The notion of lower knee extensor relative strength of women, as compared to men, may possibly extend to the hip joint musculature, although such investigations have been few and inconclusive (Cahalan, Johnson, Liu, & Chao, 1989; Donatelli, Catin, Backer, Drane, & Slater, 1991). In the event that hip and knee muscle strength demonstrates a correlation with lower extremity knee kinematics, a reduction in femoral motion control, as a result of lower hip strength, may lead to a significantly greater knee valgus angle.

Therefore, the main objectives of the present study were to determine: (a) gender differences in frontal plane knee motion during a single leg squat (SLS); (b) gender differences in hip and knee strength; and (c) the relationship between hip and knee muscle strength, and valgus knee angle during a single leg squat. The following hypotheses were made: (a) Compared to men, women will exhibit a larger absolute peak valgus knee angle, as well as increased deviation in the valgus direction during a SLS. (b) In absolute and body-mass-corrected units, women will produce less hip and knee torque compared to men. (c) There will be a negative relationship between isokinetic peak torque of the hip abductors and external rotators, and valgus knee angle during a SLS; however, no significant relationship was expected between hip flexor, hip extensor, hip adductor, hip internal rotator, knee flexor, or knee extensor strength, and valgus knee position.

Methods

Fifteen men (mean ± SD, age 26.4 ± 5.2 yrs, body mass 84.1 ± 11.8 kg, height 176.9 ± 7.1 cm) and 15 women (age 23.5 ± 3.7 yrs, body mass 66.0 ± 5.6 kg, height 170.9 ± 9.5 cm) volunteered for this study. Anyone with a history of orthopaedic injury to the lower extremity or low back, or who had cardiovascular, pulmonary, neurological, or systemic conditions that limited physical activity, were excluded from the study. Written informed consent was obtained from all participants, as approved by the Human Subjects Research and Review Committee at The University of Toledo.

Participants took part in two experimental procedures separated by approximately one week. On the first day they were evaluated for frontal plane knee movement while performing five nonconsecutive SLS. The SLS was chosen for evaluation because while it is a controlled movement, it is a dynamic maneuver that can be extrapolated from many functional activities such as landing, running, and cutting. During the second testing session the participants’ hip abduction, adduction, flexion, extension, internal rotation, external rotation, knee flexion, and knee extension strength were evaluated via isokinetic contractions.

Frontal plane knee motion, while performing a SLS, was sampled with six high-speed video cameras (Falcon, Motion Analysis Corp., Santa Rosa, CA) at a sampling rate of 60 Hz. As per manufacturers’ specifications, we performed a cube and wand calibration prior to data collection (Motion Analysis, 2000). Prior to the SLS, age and anthropometric measurements including height, body mass, femoral condyle width, foot width, ankle width, and foot length were obtained using hand-held calipers. The anthropometric measures were used with the motion analysis system to calculate segment lengths and joint angles. After each participant practiced performing a SLS on each leg, he or she then chose which leg (right or left) to use for testing.

During the SLS, the participants were barefoot and wore shorts and a short-sleeved shirt with the sleeves rolled up. Retro-reflective markers were placed with double-sided tape over the following anatomical landmarks: bilateral acromion processes, lateral humeral epicondyles, posterior wrists, anterior superior iliac spines, midlateral thighs, lateral femoral condyles, midlateral lower legs, lateral malleoli, calcanei, and head of the fifth metatarsals; a single wand marker was placed on the sacrum. For use during a 1-second static trial, four additional markers were added to the bilateral medial femoral condyles and medial malleoli.
Three-dimensional coordinates (x, y, z) were collected and digitized using the Eva system (version 6.0 software, Motion Analysis Corp.). Data paths were tracked and smoothed using a Butterworth low-pass filter with a cutoff frequency of 6 Hertz (Motion Analysis, 2000).

From the static trial, the hip joint centers were estimated by the OrthoTrak motion analysis software (version 4.2), using fixed percentages of the ASIS breadth along the x, y, and z axes. For the dynamic trials, the remaining lower extremity markers and static trial data were used to estimate knee and ankle joint centers. Joint kinematics were then calculated as Euler angles, using the coordinate system of the distal segment relative to the coordinate system of the proximal segment. These are calculated in the order of flexion/extension, varus/valgus, and internal/external rotation (Motion Analysis, 2000).

Participants squatted from a standing position to approximately 60 deg of knee flexion, and then returned to the start position. The same researcher provided all specific instructions to each participant as to the speed and depth of the squat. Participants performed 5 to 7 nonconsecutive SLSs in order to obtain 3 acceptable trials for data analysis. Acceptable trials were those in which the participant maintained balance and squatted at the desired depth of approximately 60 deg/sec of knee flexion. This SLS velocity was chosen to correspond with the isokinetic testing velocity. These criteria were subjectively applied to all participants by the same researcher. To avoid becoming fatigued, the participants received 2 minutes of seated rest between each SLS.

The participants were evaluated for (a) standing frontal plane knee position (i.e., varus/valgus) in anatomical position and in an upright single leg stance, (b) peak valgus knee position, defined as the greatest valgus angle exhibited during the single-leg squat, and (c) the change in the amount of frontal plane knee movement during the SLS (peak knee valgus minus standing frontal plane knee position). The change in frontal plane movement or excursion is a relative measurement. It does not necessarily mean that the absolute knee joint angle was in varus or valgus. Therefore, this measure identifies whether the knee was moving toward a varus or valgus direction during the SLS.

Participants were also evaluated for concentric and eccentric strength with the Biodex Isokinetic Dynamometer (Biodex Medical System, Inc., Shirley, NY) for hip abduction, adduction, flexion, extension, internal rotation, external rotation, knee flexion, and knee extension, at a preset angular velocity of 60 deg/sec. Peak torque (N·m), which is the highest torque produced through the range of motion, was determined for each muscle group and contraction mode (i.e., concentric and eccentric). Following a 5-minute submaximal warm-up on a stationary bicycle, and 4 to 5 submaximal and maximal familiarization repetitions, each participant performed 3 maximal-effort reciprocal repetitions for each muscle group and contraction mode.

Previously shown to enhance performance, visual feedback from the Biodex monitor and verbal encouragement were provided to all participants to promote maximal effort during all trials (Hald & Bottjen, 1987; Kim & Kramer, 1997; Kimura, Gulick, & Lukasiewicz, 1999; McNair, Depledge, Brettkelly, & Stanley, 1996). A minimum of 2 minutes of seated rest was provided between each set. The Biodex dynamometer was calibrated, per the manufacturer’s manual, prior to the testing of each participant. The cushion setting for all trials was in the “hard” position to minimize deceleration at the end of the range of the motion (Ling, Chen, & McDonough, 1999; Taylor, Sanders, Howick, & Stanley, 1991).

The order of strength testing for all participants was concentric/concentric followed by eccentric/eccentric abduction/adduction, flexion/extension, internal/external rotation, and knee flexion/extension. The hip motions of abduction, adduction, flexion, and extension were evaluated with participants in a standing position, and the leg was attached to the dynamometer resistance adapter with a Velcro strap just above the knee. A stable handhold was provided to ensure stability. The greater trochanter of the femur was used as the anatomical reference at which the axis of the dynamometer resistance attachment was aligned. The abduction/adduction range of motion was set using a manual goniometer from 10 deg of hip adduction to 30 deg of hip abduction.

All range-of-motion measurements were completed by the same researcher throughout the study. Peak torque was automatically corrected for gravity using Biodex Advantage software by taking a static torque measurement at approximately 30 deg of hip abduction. The hip flexion/extension contractions
were performed from a hip position of 0 degrees in the erect standing position to 60 deg of hip flexion. Gravity correction was obtained by measuring static torque at approximately 60 deg of hip flexion. To evaluate hip internal/external rotation, participants sat on an external chair facing the dynamometer resistance adapter. Velcro straps secured the lower leg just above the malleoli to the resistance adapter, and the thigh to the chair. The distal end of the thigh was aligned with the axis of rotation of the dynamometer. Range of motion was set from 10 deg of internal rotation to 10 deg of external rotation. Gravity correction was performed at 10 deg of hip internal rotation.

Previous work has demonstrated high test-retest intraclass correlation coefficients of 0.96 for standing concentric isokinetic testing of hip abduction, adduction, flexion, extension, and seated internal and external rotation at speeds of 30, 90, 150, and 210 deg/sec (Cahalan et al., 1989). To evaluate knee flexion/extension, the participants were seated with the lateral femoral epicondyle aligned with the axis of rotation of the dynamometer resistance adapter. Using Velcro straps, the lower leg was secured just above the malleoli, and the pelvis and trunk were stabilized. The knee flexion/extension range of motion was preset to include the range of 10 to 60 deg of knee flexion. Gravity correction torque was measured at 10 deg of knee flexion. Previous test-retest reliability studies have shown isokinetic testing of the knee to have high intraclass correlation coefficients (Pincivero, Lephart, & Karunakara, 1997b).

Gender differences for maximal effort peak torque were examined using absolute units (N-m), and body mass relative units (N-m·kg⁻¹). An independent t-test was used to determine gender differences in concentric and eccentric absolute and body-mass-normalized peak torque for both hip and knee strength, and standing frontal plane knee position, peak knee valgus, and the change in frontal plane knee movement. An alpha level of 0.05 was used for all t-tests.

In this study, factor analysis was used to detect potential correlations between body mass relative concentric and eccentric abduction/adduction, flexion/extension, internal/external rotation, and knee flexion/extension peak torques. Principal-components analysis is a statistical method derived from matrix algebra, designed to reduce the number of variables based on a matrix of correlations between the measured variables (Munro, 1997). For data reduction, the principal components extraction method and varimax rotation with Kaiser normalization were used.

Because of high correlations between strength variables, three principal components were defined: the hip factor, the knee factor, and the rotation factor. These three factors were named based on high loadings of specific strength variables, thus representing the name of each factor. These three principal components then became new independent variables used for subsequent regression analysis. The dependent variables measured were standing frontal plane knee position, peak knee valgus, and the change in frontal plane movement. Gender was factored into the regression model as a coded variable (“1” for males, “2” for females). Additionally, linear regression was performed separately for each strength and kinematic variable. A Pearson product moment correlation matrix was produced to examine relationships between each strength variable and each kinematic variable. For all regression and correlation analyses, a preset alpha level of 0.05 was used.

Results

In anatomical position, men and women presented with a slightly varus knee position (mean ± SD, men = 1.95 ± 4.07 deg, women = .63 ± 2.01 deg). Concurrently, in single leg stance men and women also presented with a varus knee orientation (1.63 ± 3.35 deg and 1.73 ± 2.7 deg, respectively). During the SLS, the peak knee flexion angle for men and women was 62.45 ± 9.56 deg and 65.89 ± 7.79 deg, respectively. When performing the single-leg squat, women demonstrated a peak knee valgus angle of 3.67 ± 4.58 degrees, and men showed a peak knee valgus angle of 2.75 ± 5.27 deg. A peak knee varus of 6.48 ± 4.45 for men and 3.85 ± 2.78 for women was presented. There were no significant gender differences for all measurements of frontal plane knee kinematics (p > 0.05).

Absolute and body-mass-normalized peak torque values for concentric and eccentric hip abduction, adduction, flexion, extension, internal rotation, external rotation, knee flexion, and knee extension are listed in Figures 1 and 2. The results demonstrated that men generated significantly
greater absolute peak torque than women for all strength measurements \(p < 0.05\) except eccentric internal rotation. When normalized to body mass, men generated significantly greater peak torque than women for concentric hip adduction, flexion, knee flexion and knee extension, and eccentric hip extension \(p < 0.05\).

Derived from the principal components analysis were the hip, knee, and rotation factors. Together, the three principal components accounted for 74.3\% of the total variance represented by all the strength variables. The hip, knee, and rotation factors individually account for 55\%, 10.6\%, and 8.7\% of the variance, respectively. The loadings for each variable within each factor are listed in Table 1.

Linear regression analysis revealed that concentric abduction \(r^2 = 0.13, \text{SEE} = 8.11\), knee flexion \(r^2 = 0.18, \text{SEE} = 7.88\), and knee extension \(r^2 = 0.14, \text{SEE} = 8.10\) peak torque were significant predictors \(p < 0.05\) of frontal plane motion of the knee during a SLS. Concurrently, a Pearson product moment correlation demonstrated weak to moderate, but significant, negative relationships between the concentric abduction \(r = -0.37, p < 0.05\), knee flexion \(r = -0.43, p < 0.001\), and knee extension \(r = -0.37, p < 0.05\) peak torque and frontal plane knee motion (Table 2). These data suggest that individuals with greater strength of these muscle groups tend to demonstrate a lower amount of knee movement in the valgus direction. Peak torque was not a significant predictor of either standing knee valgus or peak knee valgus angle.

When considering all strength variables collectively in the factor analysis, regression analyses demonstrated that only the knee factor \(r^2 = 0.22, \text{SEE} = 7.85\) was a significant predictor of frontal plane knee motion (Table 1). When interpreting the knee factor, strength of all the hip and knee motions...
Figure 2 — Means for body-mass-normalized peak torque values by gender at a testing velocity of 60 deg/sec. Light bars, men; dark bars, women.

Discussion

In partial support of the first hypothesis, the major findings of this study demonstrated that hip abduction, knee flexion, and knee extension strength were significant predictors of frontal plane knee movement during a single leg squat. Additionally, when all strength variables were considered together in the principal components analysis, hip abduction, hip internal rotation, knee flexion, and knee extension strength were the strongest predictors of frontal plane knee motion. Furthermore, significant negative correlations between these strength variables and movement in the valgus direction demonstrated that as strength increased, the degree of motion in the valgus direction decreased. Rejecting the second hypothesis, there were no significant gender differences in standing frontal plane knee position, peak knee valgus, or frontal plane movement. Significant gender differences were observed for all absolute strength values, except eccentric internal rotation, as well as body-mass-normalized concentric adduction, hip flexion, knee flexion, knee extension, and eccentric hip extension peak torques, partially supporting the third hypothesis.

Mechanisms of neuromuscular control in the frontal plane have typically been investigated using open kinetic chain perturbation protocols. Andriacchi, Andersson, Ortengren, and Mikosz (1984), and Lloyd and Buchanan (2001) observed that co-contraction of the quadriceps femoris and hamstring muscles occurred to stabilize varus/valgus knee movement. In the present study, knee extensor and flexor strength explained 13.6% and 18.1% of the variability, respectively, when predicting frontal plane knee movement. Although a small amount of variability was explained by the strength measure-
ments, the present results are supported by previous data in which quadriceps femoris and hamstring muscle contribution to knee varus/valgus control accounted for approximately 14% of the variance (Lloyd & Buchanan, 2001).

In addition to open kinetic chain perturbation protocols, the role of quadriceps femoris and hamstring muscle strength to varus and valgus movement control has also been demonstrated during functional weight bearing activities (Augustsson & Thomee, 2000; Pincivero, Lephart, & Karunakara, 1997a). Hewett et al. (1996) observed that increased quadriceps femoris and hamstring muscle strength decreased frontal plane knee moments during the landing phase of a drop jump. Because of small abduction and adduction moment arms of these two muscle groups, it remains unclear what mechanisms these muscle groups employ for knee varus/valgus movement control. It may be speculated that thigh muscle co-contraction reduces varus/valgus knee movement via long-latency reflex-mediated increases in joint compression and stiffness (Dhaher, Tsoumanis, & Rymer, 2003; Lloyd & Buchanan, 2001).

Other studies have also suggested that frontal plane knee movement control may be provided by the hip abductor and adductor muscles (Andriacchi et al., 1984; Lloyd & Buchanan, 2001). Additionally, it has been suggested that athletes with stronger hip abductors and external rotators may not sustain serious acute or overuse knee injuries (Ireland, Willson, Ballantyne, & McClay Davis, 2003; Leetun, Ireland, Willson, Ballantyne, & McClay Davis, 2005). The present study found that increased hip abductor strength significantly decreased frontal plane knee motion in the valgus direction, suggesting an important role of this muscle group in providing knee stabilization.

Several studies have demonstrated that women exhibit greater knee valgus angles during dynamic tasks when compared to men (Hewett et al., 1996; Malinzak et al., 2001; Markolf et al., 1995). Malinzak et al. (2001) measured gender differences in knee valgus angle during running, cross-cutting,
and side-step cutting maneuvers, and observed that women exhibited a greater valgus knee angle than men (mean difference of 11 deg). However, the motion patterns appeared to be similar between men and women, suggesting that women started in a more valgus position and thus remained in that orientation throughout the tasks, as was reported during a single-leg squat by Zeller et al. (2003).

Similar results of greater valgus knee angles in women compared to men during jumping tasks were observed by Ford et al. (2003) and Chappell et al. (2002). Valgus knee angle during running and side-step cutting were observed by McLean et al. (1999), and unlike Malinzak et al. (2001), gender differences were not demonstrated during straight ahead running. These two studies did concur that women demonstrated greater knee valgus angles than men throughout the entire side-step cutting maneuver. As with Malinzak et al. (2001), there were no gender differences between the range-of-motion patterns observed by McLean et al. (1999), but only between minimum and maximum valgus knee angles.

Based on previous studies (Malinzak et al., 2001; McLean et al., 1999; Zeller et al., 2003), it was hypothesized that women would exhibit greater valgus knee angles than men during performance of the single-leg squat. However, the results of the present study did not support this hypothesis. This may be explained by the probable fact that a single leg squat may not produce the magnitude of external moments that a high-speed cutting or jumping maneuver would. Therefore, it is possible that the imposed moments in this study were not large enough to elicit gender differences in peak knee valgus angles.

It has been shown that applying a valgus load to the knee, particularly in combination with anterior tibial translation, amplifies ACL strain (Berns et al., 1992; Markolf et al., 1995). However, normative data for frontal plane anatomical alignment either in stance or during a dynamic activity have not been well established. Furthermore, it is unclear whether ACL strain is increased by virtue of frontal plane knee position or simply by applying a valgus load. Therefore, the clinical value of peak knee valgus angle remains undefined (McLean et al., 1999). As a result, it may be argued that adding a valgus load to a knee with a naturally varus orientation may cause increased ligamentous strain without actually attaining a true valgus knee position. Consequently, in the current study the most practical findings with regard to the relationship between strength and frontal plane knee kinematics may be related to the change of knee motion in the valgus direction, regardless of the absolute valgus knee angle.

The results of the present study concurs with previous studies, that men produce greater absolute and body-mass-relative knee extensor and flexor torque than women (Hakkinen et al., 1997; Hewett et al., 1996; Huston & Wojtys, 1996; Kanehisa et al., 1996; Pincivero et al., 2003). Specifically, Pincivero et al. (2003) observed significantly greater knee extensor and flexor peak torque values (body mass relative) in 19 men, as compared to 20 women, performing maximal-effort contractions at 60 deg/sec. When normalized to quadriceps femoris muscle cross-sectional area, Kanehisa et al. (1996) found significantly greater mean knee extensor torque over 5 maximal-effort contractions at 180 deg/sec. These previous findings, in addition to those of the current study, indicate that the small yet significant role of the knee extensors and flexors in reducing frontal plane knee motion may be different between men and women.

Although isokinetic testing of the hip in the standing position has been limited, the results of the present study agree with the findings of Cahalen et al. (1989). While direct comparisons of peak torque between studies is impractical because of different testing speeds, both studies concurred that women produced less absolute peak torque than men for the hip abductors, adductors, flexors, extensors, internal rotators, and external rotators. Normalizing hip and thigh strength to body mass attenuated the gender differences for all muscle groups except hip adduction, flexion, and extension, and knee flexion and extension. If women display lower relative strength, a predisposition to increased valgus knee motion may be present, which may be a contributing factor underlying the high incidence of ACL injury.

The major findings of the present study suggest that the action of the hip abductor, quadriceps, and hamstring muscles may play a significant role in controlling frontal plane knee movement. During the single leg squat, the hip abductor muscles may function to stabilize the femur, thus decreasing hip adduction and reducing valgus knee excursion. Additionally, the quadriceps femoris and hamstring muscle co-contraction may work to increase joint
stiffness (Dhaher et al., 2003; Lloyd & Buchanan, 2001). Because the hip and knee muscles together accounted for nearly 22% of the variability in predicting movement of the knee in the frontal plane, it illustrates the importance of including strengthening exercises for the hip joint muscles in a lower extremity conditioning program for athletes. As women exhibited less quadriceps femoris and hamstring muscle strength than men when normalized for body mass, it may be important to also focus on strength development for these muscle groups, which may enhance knee joint stiffness and control of the knee in the frontal plane during weight-bearing athletic activities.

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