RELATIONSHIP BETWEEN FORCE PRODUCTION DURING ISOMETRIC SQUATS AND KNEE FLEXION ANGLES DURING LANDING

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ABSTRACT

Fisher, H, Stephenson, ML, Graves, KK, Hinshaw, TJ, Smith, DT, Zhu, Q, Wilson, MA, and Dai, B. Relationship between force production during isometric squats and knee flexion angles during landing. *J Strength Cond Res* 30(6): 1670–1679, 2016—Decreased knee flexion angles during landing are associated with increased anterior cruciate ligament loading. The underlying mechanisms associated with decreased self-selected knee flexion angles during landing are still unclear. The purpose of this study was to establish the relationship between the peak force production at various knee flexion angles (35, 55, 70, and 90°) during isometric squats and the actual knee flexion angles that occur during landing in both men and women. A total of 18 men and 18 women recreational/collegiate athletes performed 4 isometric squats at various knee flexion angles while vertical ground reaction forces were recorded. Participants also performed a jump-landing-jump task while lower extremity kinematics were collected. For women, significant correlations were found between the peak force production at 55 and 70° of knee flexion during isometric squats and the knee flexion angle at initial contact of landing. There were also significant correlations between the peak force production at 55, 70, and 90° of knee flexion during isometric squats and the peak knee flexion angle during landing. These correlations tended to be stronger during isometric squats at greater knee flexion compared with smaller knee flexion. No significant correlations were found for men. Posture-specific strength may play an important role in determining self-selected knee flexion angles during landing for women.

KEY WORDS: ACL, strength, biomechanics, kinematics, kinetics

INTRODUCTION

An estimated 200,000 anterior cruciate ligament (ACL) tears occurred in the United States in 2012, causing a collective lifetime expense between $7.6 and $17.7 billion annually (27). When the injury rate is normalized to sports exposures, women are 2–4 times more likely to tear their ACL during sports involving landing and cutting maneuvers (1,36). Efforts have focused on understanding ACL injury mechanisms and risk factors, and investigators have identified knee flexion angle as an important component in preventing ACL injuries (10,12,45). Although not being identified as the most sensitive variable to predict ACL injuries, the peak knee flexion angle during landing was smaller for injured athletes compared with uninjured athletes in 1 prospective study in adolescent female athletes (21). Another prospective study has shown that restricted trunk, hip, and knee flexion range of motion during landing may increase ACL injury risks in youth soccer athletes (34).

Furthermore, video analysis of ACL injury events has shown that individuals' knees typically demonstrate decreased flexion near the time of injury and the estimated time of ACL injury is within 100 milliseconds after initial ground contact (14,23,24,42). Investigators have quantified in vivo ACL strain during a jump-landing task using a combined videographic, fluoroscopic, and magnetic resonance imaging technique and have found a negative correlation between the knee flexion angle and ACL strain (40). Anterior cruciate ligament strain reached its peak when the knee flexion angle was the smallest (40). Using the same technique, investigators have shown that landing with an increased knee flexion angle at initial contact could decrease peak ACL strain during jump landing (7). In addition, landing with an increased peak knee flexion angle allows individuals to dissipate impact ground reaction forces with a greater joint range of motion and a longer period and is associated with decrease peak impact ground reaction forces, which are associated with decreased ACL loading (13,15,44). Consequently, numerous studies designed to decrease ACL injury risks through modifying jump-landing

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techniques have included increasing knee flexion angles as an important component and shown that knee flexion angles may be increased through immediate feedback (13,17,32) or neuromuscular training (20,29,33).

The underlying mechanisms associated with decreased self-selected knee flexion angles during landing, however, are still unclear. Although individuals can deliberately increase their knee flexion angles during landing, this increase is usually associated with decreased performance including decreased jump height and increased stance time (13,32) and may not be considered a true learning effect (4). Understanding the underlying mechanisms of self-selected decreased knee flexion angles during landing may provide insight into training individuals to enhance their physical capability to increase knee flexion without compromising performance. Previously, investigators have hypothesized a relationship between lower extremity strength and landing mechanics. However, although some studies have indicated that lower extremity strength may affect knee flexion angles during landing (6,25), others have found that lower extremity strength is a poor indicator of landing mechanics (5,8,30,39). One factor that may contribute to these inconsistent findings is the different methodologies and associated limitations for assessing lower extremity strength.

Quadriceps and hamstring strength has been commonly assessed isokineticly or isometricly during open-chain exercises when individuals are in a seated or prone posture (5,6,25,31,38,39). The advantage of these assessments is the isolation of muscle groups, but most assessments fail to simulate a closed-chain and relatively upright posture during landing. Wilson et al. (41) highlighted the importance of posture in determining the transfer effect between training exercises and strength testing protocols. The investigators found that squat training resulted in more than 20% strength gain in maximum squat and vertical jump height but no change in isokinetic knee extension torques. Another limitation of previous strength assessments is that the peak force/torque production is extracted at a single joint angle, which does not consider the muscle force-length or joint force-angle relationships. Investigators have demonstrated that force production generally decreases as the knee flexion angle increases during isometric squats (35,46) and training may modify the joint force-angle relationship (2,41,46). During a landing task, the knee joint goes through a range of motion from initial contact and maximum flexion, and the knee flexion angle at different time points of landing typically varies between 10 and 100° (16,19). Increasing knee and hip flexion is likely to increase the mechanical moment arms from the vertical ground reaction force to the knee and hip joint centers and subsequently impose greater moments on these joints (35). Although deep knee flexion is commonly encouraged to decrease ACL loading, it may require greater strength to reach such a posture during landing. By assessing strength at different knee flexion angles, it may be possible to quantify the angle-specific strength used during landing.

Therefore, the purpose of this study was to establish the relationship between the peak force production at various knee flexion angles (35, 55, 70, and 90°) during isometric squats and the actual knee flexion angle occurring at initial contact, and the peak knee flexion angle occurring during landing. Isometric squats were used to provide a better assessment of the dynamic strength used during landing. The force production was measured at different knee flexion angles during isometric squats to assess the joint angle-specific strength. It was hypothesized that the peak force

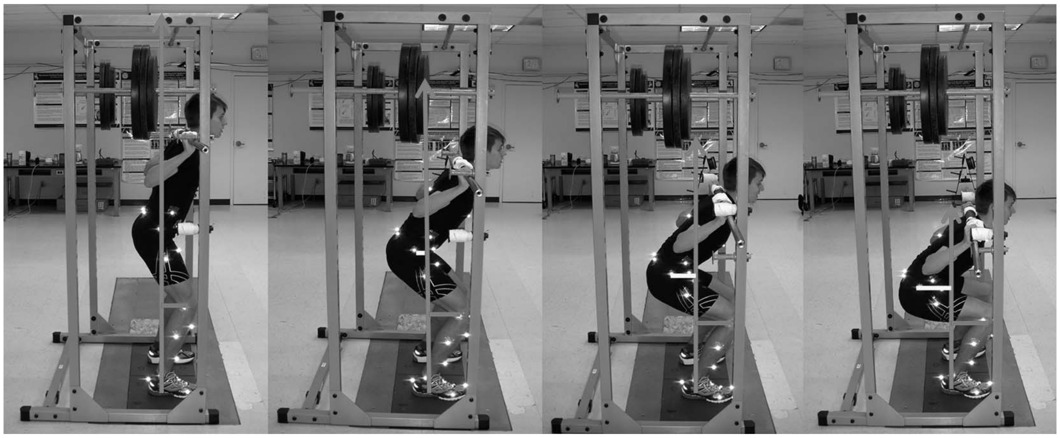

Figure 1. Isometric squats at different knee flexion angles. The red vector indicates the vertical ground reaction force. The green line indicates the moment arm from the vertical ground reaction force to the knee. The yellow line indicates the moment arm from the vertical ground reaction force to the hip.

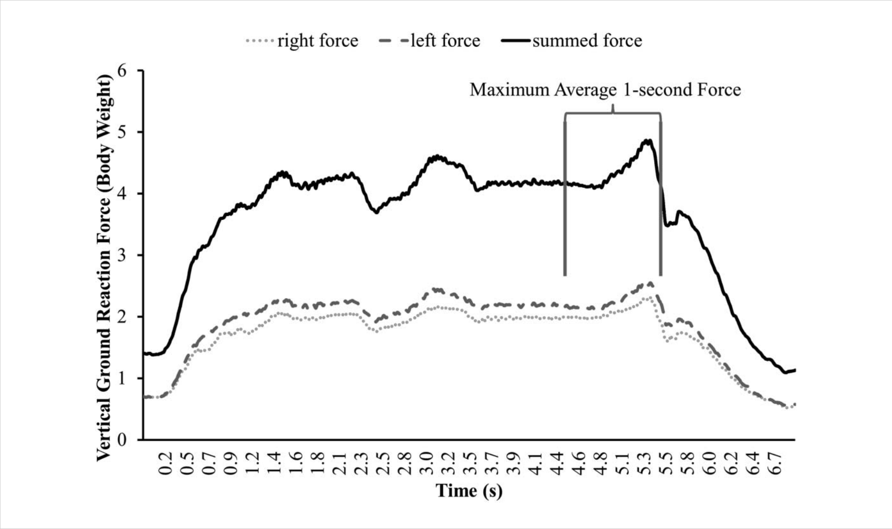

Figure 2. Vertical ground reaction force during an isometric squat.

production during isometric squats would be positively correlated with the knee flexion angle at initial contact and peak knee flexion angle during landing in both men and women.

METHODS

Experimental Approach to the Problem

This study used a correlation analysis to quantify the relationship of the peak force production at different knee flexion angles during isometric squats and the knee flexion angle at initial contact and peak knee flexion angle during landing in both men and women. Recreational/collegiate athletes performed 4 isometric squats against an immovable bar while vertical ground reaction forces were recorded using 2 force platforms. Participants started the isometric squats at 4 knee flexion angles (35–45, 55–65, 75–85 and 95–105°), which were distributed within the typical knee joint range of motion during landing (16,19). Knee flexion angles of 15–25° were not included because pilot testing showed that participants tend to fully extend their knees during isometric squats when the starting knee flexion angle was 20°. Observation of actual knee flexion angles during isometric squats revealed relatively large differences from the targeted starting knee flexion angle. Therefore, a regression approach was used to predict the peak force production at knee flexion angles of 35, 55, 70, and 90° during isometric squats. Participants also performed a jump-landing-jump task while lower extremity kinematics were collected using high-speed cameras to calculate knee flexion angles during landing. Pearson correlation tests were performed between the peak force production at each knee flexion angle during isometric squats and the initial and peak knee flexion angles during landing for men and women, separately. Men and women were analyzed separately the relationship between lower extremity strength and landing biomechanics may differ between women and men (26,32).

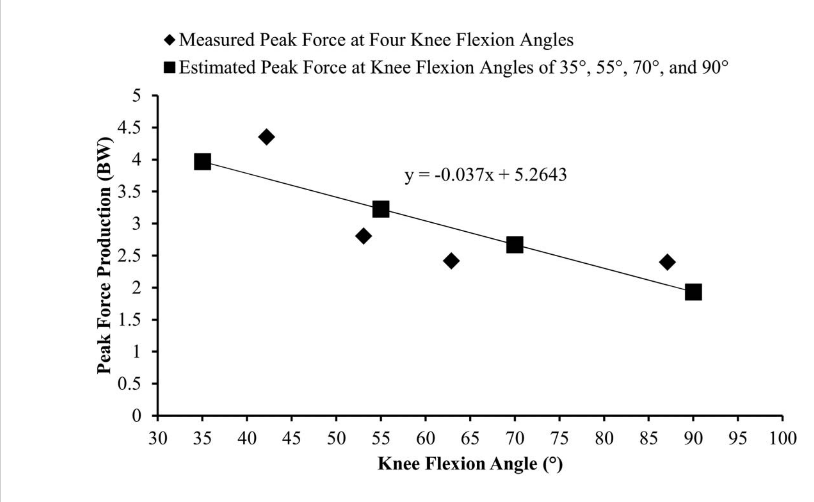

Figure 3. Regression of peak force production as a function of knee flexion angle during squats for participant 1. BW = body weight.

Subjects

Examination of preliminary data indicated a strong correlation between the peak force production at large knee flexion angles and peak knee flexion angle during landing. Assuming a coefficient of determination of 0.6 for Pearson correlation analysis, a sample size of 17 was needed for a type I error at the level of 0.05 to achieve a power of 0.8. A total of 18 male (age: 21.2 ± 1.8 years; height: 1.83 ± 0.08 m; mass: 81.6 ± 17.9 kg) and 18 female (age: 19.8 ± 1.5 years; height: 1.65 ± 0.08 m; mass: 61.5 ± 7.7 kg) recreational/collegiate athletes with experience in playing sports that involved

Table 1. Descriptive data of force production and knee flexion angles during isometric squats and landing (mean ± *SD*).*†

	Males	Females
Measured knee flexion angle during squat 1 (°)	37.2 (12.3)	38.0 (11.2)
Measured knee flexion angle during squat 2 (°)	58.6 (10.2)	54.7 (7.5)
Measured knee flexion angle during squat 3 (°)	72.6 (8.3)	67.4 (7.5)
Measured knee flexion angle during squat 4 (°)	89.6 (12.4)	85.7 (14.4)
Measured peak force during squat 1 (BW)	3.80 (0.94)	2.96 (0.56)
Measured peak force during squat 2 (BW)	3.20 (1.05)	2.54 (0.49)
Measured peak force during squat 3 (BW)	2.38 (0.63)	2.05 (0.32)
Measured peak force during squat 4 (BW)	2.12 (0.40)	1.80 (0.20)
Estimated peak force at knee flexion angle of 35° during squat (BW)	3.83 (0.93)	3.09 (0.62)
Estimated peak force at knee flexion angle of 55° during squat (BW)	3.19 (0.73)	2.49 (0.46)
Estimated peak force at knee flexion angle of 70° during squat (BW)	2.71 (0.61)	2.04 (0.45)
Estimated peak force at knee flexion angle of 90° during squat (BW)	2.07 (0.50)	1.51 (0.47)
Knee flexion angle at initial contact during landing (°)	26.1 (4.94)	24.0 (9.5)
Peak knee flexion angle during landing (°)	91.00 (13.1)	90.6 (11.4)

*BW = body weight.
†Squat 1, 2, 3, and 4 were performed with starting knee flexion angles of 35–45°, 55–65°, 75–85°, and 95–105°, respectively.

jump-landing tasks participated in this study. Sports experience was defined as currently playing sports at least 1 time per week or having previously played at high school, college, or club levels. Participants were physically active and participated in sports and exercise at least 2 times per week for a total of 2–3 hours per week. Participants were excluded if they 1.) had no experience in playing sports that involve jump-landing tasks, 2.) were not physically active, 3.) had an ACL injury or other major lower extremity injuries which involved surgical procedures, 4.) had a lower extremity injury that prevented participation in physical activity for more than 2 weeks over the previous 6 months, or 5 possessed cardiovascular, respiratory, neurologic, or other conditions that prevented them from participating at maximal effort in sporting activities. The age range for all subjects in this study was between 18 and 25 years old. Permission to conduct this study was obtained from the University of Wyoming Institutional Review Board. Participants signed informed consent forms as adult participants before participation. The study conforms to the Code of Ethics of the World Medical Association (approved by the ethics advisory board of Swansea University) and required players to provide informed consent before participation.

Procedures

Participants wore spandex shorts, shirts, and standard running shoes (Ghost 5, Brooks Sports, Bothell, WA, USA). Participants conducted a warm-up protocol including 5-minute running at a self-selected pace on a treadmill, followed by 10 body weight (BW) squats, 10 BW lunges, and 10 squats with an unloaded 12-kg barbell. The testing side (left or right leg) for kinematic analysis was randomly selected because a previous study has

Table 2. Pearson correlation coefficients (*p* values) between peak force production during isometric squats and knee flexion angles during landing for men and women, respectively.*

	Peak force at knee flexion angle of 35° during squat	Peak force at knee flexion angle of 55° during squat	Peak force at knee flexion angle of 70° during squat	Peak force at knee flexion angle of 90° during squat
Knee flexion angle at initial contact during landing	M: 0.156 (0.536), F: 0.496 (0.036)	M: 0.187 (0.457), F: 0.640 (0.004†)	M: 0.216 (0.388), F: 0.651 (0.003†)	M: 0.250 (0.318), F: 0.495 (0.037)
Peak knee flexion angle during landing	M: 0.245 (0.327), F: 0.399 (0.101)	M: 0.225 (0.370), F: 0.609 (0.007†)	M: 0.194 (0.441), F: 0.694 (0.001†)	M: 0.112 (0.659), F: 0.581 (0.012)

*M = males; F = females.
†A significant correlation at an adjusted type I error rate.

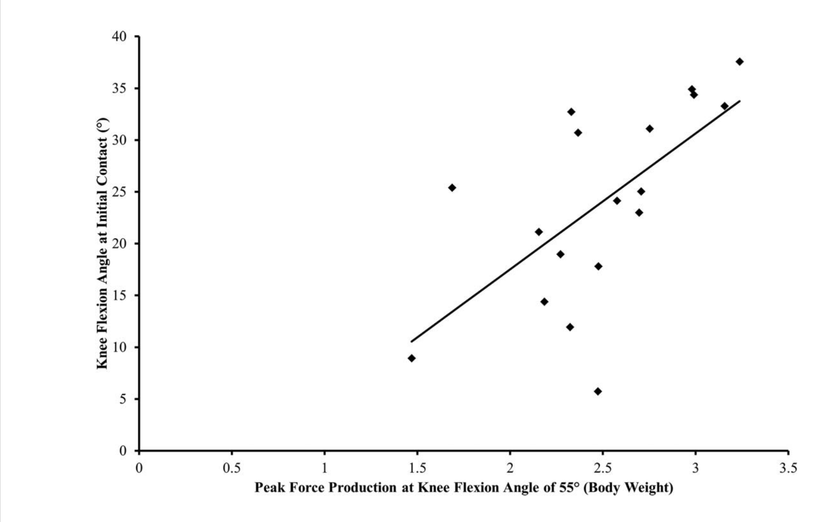

Figure 4. Linear correlation between peak force production during squat at knee flexion angle of 55° and knee flexion angle at initial contact during landing in women.

suggested a small difference in bilateral knee flexion angles during a vertical landing task (18). A total of 26 retroreflective markers were placed on participants' bony landmarks of the trunk, pelvis, and the testing leg (11,16). The 3 dimensional trajectories of these retroreflective markers were captured using 8 opto-reflective cameras at a sampling frequency of 160 Hz. (Vicon Bonita 10, Oxford Metrics Ltd, Oxford, UK).

Participants performed a jump-landing-jump task, which incorporated vertical and horizontal movements as participants jumped from a 30-cm high box forward a distance of 50% of their height away from the box such that the foot of testing side landed on a force platform and immediately rebounded for a maximal vertical jump on landing (6,11). A force platform (4060-10; Bertec, Columbus, OH, USA) was used to collect the unilateral force participants exerted on the ground at a sampling frequency of 1,600 Hz. Participants were instructed to focus on jumping as high as they could during the second jump. Participants performed 2 practice trials (more practice trials were allowed when needed), before performing 3 recorded trials, with a 30-second rest between trials (37).

After the landing task, participants performed a total of 4 maximal isometric squats at 4 different knee flexion angles using a squat rack and a barbell (Figure 1). Participants started the squats at 4 knee flexion angles (35–45, 55–65, 75–85, and 95–105°), which were achieved by manipulating the locations of the bar catch pins in the squat rack. Participants were asked to bend their knees to lower their shoulders to a certain height defined by 2 removable pins in the squat rack to define the relationship between the pin height and knee flexion angle at that height. When lowering their bodies, participants were allowed to bend their ankle, hip, and trunk using their preferred movement patterns. However, participants were instructed to avoid excessive hip and trunk flexion to decrease the risk of injury. By identifying 3 markers; greater trochanter, lateral femoral condyle, and lateral malleolus of the testing leg, the knee flexion angle was calculated in real-time using the Vicon Nexus software. Participants performed a number of preliminary trials with a plastic bar to obtain the necessary knee flexion angles for different heights of the pins. Once knee flexion angles were identified, participants performed a maximal contraction against the immovable bar. During the isometric squat, participants stood with feet shoulder width apart and held onto the bar. Participants were instructed to extend the lower extremities and trunk

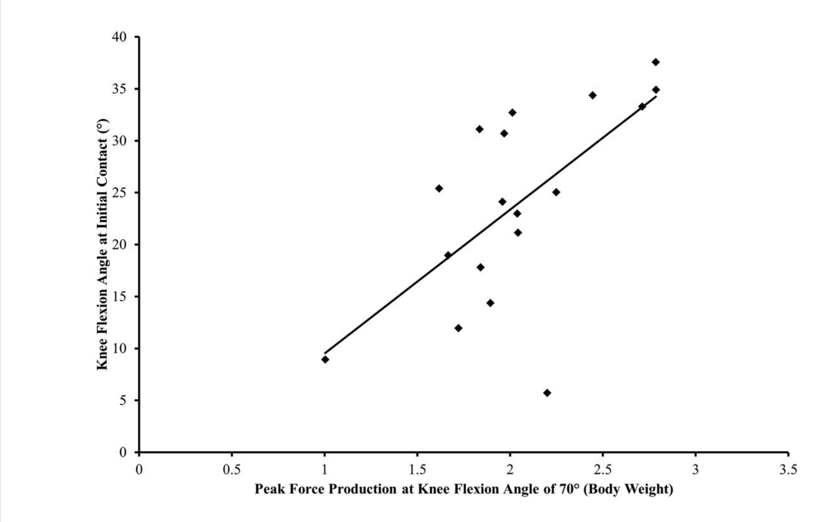

Figure 5. Linear correlation between peak force production during squat at knee flexion angle of 70° and knee flexion angle at initial contact during landing in women.

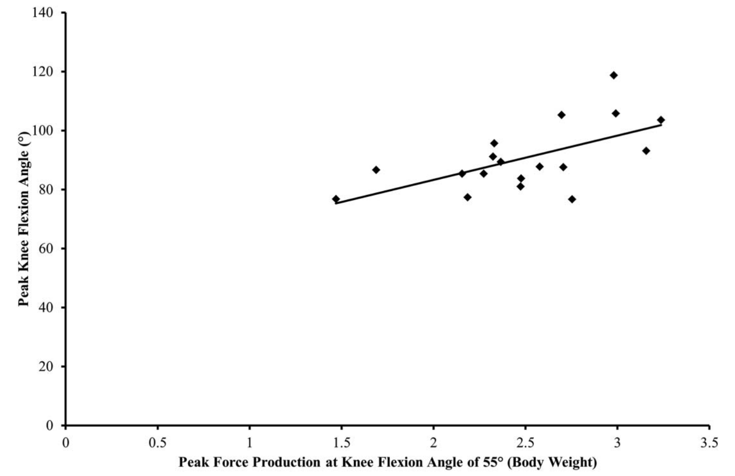

Figure 6. Linear correlation between peak force production during squat at knee flexion angle of 55° and peak knee flexion angle during landing in women.

as hard as possible without lifting their heels off the ground. Investigators provided consistent verbal encouragement including "push harder" and "go, go, go" during the isometric squat. For each knee angle, participants were coached to reach maximal force generation within 2 seconds and then were required to hold the position for a total of 3 more seconds when an investigator was counting 1, 2 and then 1, 2, 3 with an interval of 1 second. A recovery time of 3 minutes was used between each maximal effort (28). Two force platforms were used to collect the bilateral vertical ground forces.

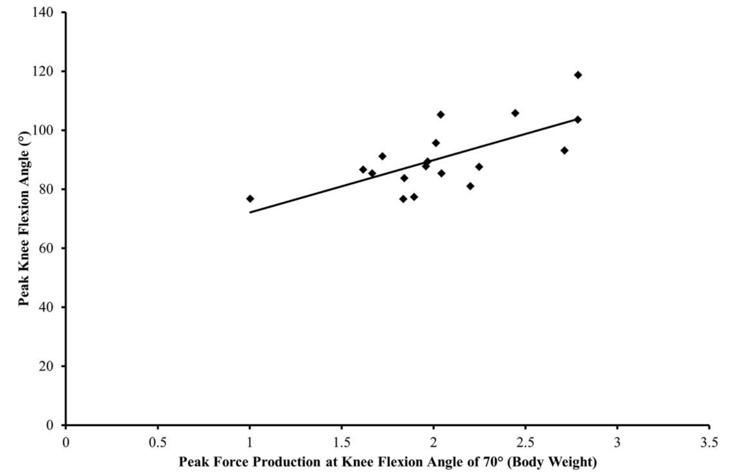

Figure 7. Linear correlation between peak force production during squat at knee flexion angle of 70° and peak knee flexion angle during landing in women.

Data Reduction

Marker coordinates and vertical ground reaction forces were filtered using a fourth-order, zero-phase-shift Butterworth filter at a low-pass cutoff frequency of 15Hz (11,16) and 100 Hz (22), respectively. Knee flexion angles for the testing side were calculated as the angle between the greater trochanter, lateral femoral condyle, and lateral malleolus markers. For the isometric squats, the bilateral vertical ground forces were summed from the 2 force plates with the consideration of bilateral asymmetry and subsequently normalized to BW. The peak average summed vertical ground reaction force during a period of 1 second at each knee flexion angle was calculated (Figure 2). The actual knee flexion angle when the peak force was produced during each isometric squat was quantified. For the landing task, the knee flexion angle at initial ground contact as indicated by a vertical ground reaction force greater than 20 N (26) and the peak knee flexion angle during the stance phase were extracted for analysis.

Statistical Analyses

Observation of actual knee flexion angles during isometric squats revealed relatively large differences from the targeted starting knee flexion angle. These differences were likely attributed to the errors between calibration and official testing trials, and participants' motion and soft tissue deformation during the isometric squats. To overcome this limitation, a linear regression was performed between the actual knee flexion angle and peak force production during 4 different squats for each participant. The estimated peak force production at knee flexion angles of 35, 55, 70, and 90° was used for further analysis (Figure 3). This regression approach was supported by previous literature (35,46), which has shown a close-to-linear relationship between

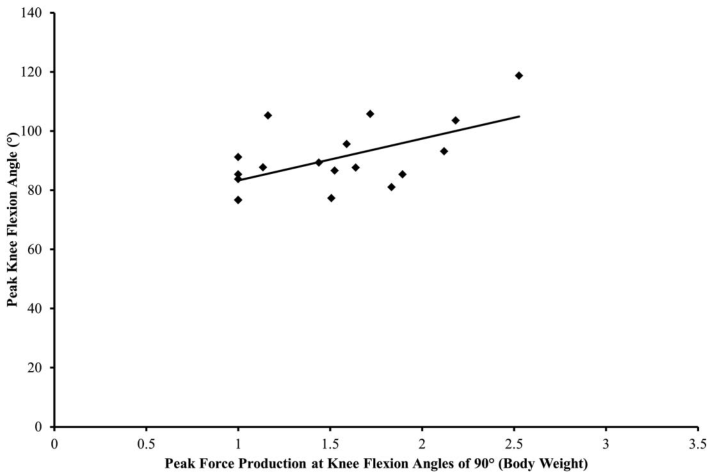

Figure 8. Linear correlation between peak force production during squat at knee flexion angle of 90° and peak knee flexion angle during landing in women.

the knee flexion angle and peak isometric force production during isometric squats when the knee flexion angle was between 20 and 100°. The minimal estimated peak force was constrained to be 1 body weight.

To quantify the relationship between the peak force production during squats and knee flexion angles during landing, Pearson correlation tests were performed between the estimated peak force production at knee flexion angles of 35, 55, 70, and 90° during isometric squats and the initial and peak knee flexion angles during landing for men and women, separately. Visual inspection of scatter plots indicated a linear relationship. A total of 16 correlation analyses were performed. The Benjamini and Hochberg's method (3) was used to control the study-wise false discovery rate to be 0.05. Correlations less than 0.3 were considered weak. Correlations between 0.3 and 0.5 were considered moderate. Correlations greater than 0.5 were considered strong (9). Statistical analyses were performed using the IBM SPSS Statistics 22 software (IBM Corporation, Armonk, NY, USA).

RESULTS

Data of 2 isometric squats were missing because of technical errors. For these 2 participants, linear regressions were performed with 3 instead of 4 data points. Descriptive data of measured peak force production and knee flexion angles during isometric squats, estimated peak force production during squats, and knee flexion angles during landing are presented in Table 1. The mean and *SD* of R^2 of linear regressions of the peak force production as a function of the knee flexion angle during isometric squats were 0.81 and 0.16, respectively.

After the adjustment for the study-wise false discovery rate, the largest p value for a significant correlation was 0.012. As shown in Table 2, for men, no significant correlations were found. For women, significant and strong correlations were found between the knee flexion angle at initial contact of landing and estimated peak force production at knee flexion angles of 55° and 70° during isometric squats (Figures 4, 5). Significant and strong correlations were also observed for women between the peak knee flexion angle during landing and estimated peak force production at knee flexion angles of 55°, 70°, and 90° during isometric squats (Figures 6, 7, 8).

DISCUSSION

Knee flexion angle has been identified as an important loading mechanism of the ACL (10,12,45). To identifying the underlying mechanism of decreased self-selected knee flexion angles during landing, this study attempted to establish the relationship between force production at various knee flexion angles during isometric squats and the actual knee flexion angles that occur during landing. The results partially support the hypothesis by showing that positive correlations exist between force production during isometric squats and knee flexion angles during landing in women, but not in men.

Previously, inconsistent findings were observed for the relationship between lower extremity strength and landing mechanics (5,6,8,25,30,39). Boling et al. (6) found that individuals who developed patellofemoral pain syndrome demonstrated decreased knee flexion angles and isometric quadriceps and hamstring strength compared with controls during baseline testing in a prospective cohort study. Lephart et al. (25) observed that women had less isokinetic quadriceps and hamstring strength and smaller knee flexion angles during both single-leg landing and hop tasks. The findings of these 2 studies indicate that lower quadriceps and hamstring strength may be related to decreased knee flexion angles during landing. However, Beutler et al. (5) found very weak correlations between isometric strength of the lower extremity and Landing Error Scoring System scores, which were determined by a count of landing technique errors based on frontal plane and sagittal plane views of landing patterns. Mizner et al. (30) showed that trunk and lower extremity strength seemed to be a poor predictor of the changes in landing mechanics after landing instruction. Shultz et al. (39) found that quadriceps and hamstring isometric strength and activation were poor predictors of knee and hip flexion angles during landing in both men and women. The results of these 3 studies tend to indicate a lack of association between lower extremity strength and landing mechanics. One limitation of previous studies is that lower extremity strength was assessed in a sitting or prone posture. In a more recent study, Carcia et al. (8) used a leg-press task to quantify lower extremity strength to more closely represent the posture during a landing task. However, this task was performed in a seated position, and no relationship was found between the force production during the leg-press and knee flexion angles during early landing in women. Previously, investigators have shown high specificity in strength gain between the training and testing tasks, and posture has been shown to play an important role in the transfer of training results (43). As such, to overcome the lack of consideration of posture in strength assessment in previous studies, the current investigators used isometric squats to better represent the strength used during landing. The force production during isometric squats was the resultant force generated by the trunk and lower extremity. Although the strength of each joint was not isolated, the resultant force may be a more realistic assessment because of the dynamic nature of a jump-landing task. The findings indicated that women who demonstrated decreased knee flexion angles during landing also had lower isometric squat force production.

The positive correlation between the force production during isometric squats and knee flexion angles during landing was only observed in women. Literature has documented that men exhibit greater strength than women (5,25,31,38), but the correlation between lower extremity strength and landing mechanics may differ between men and women. Schmitz and Shultz (38) observed that isometric knee extensor strength positively correlated with knee energy absorption during landing in women, but not in men. Similarly, Montgomery et al. (31) found positive correlations between lower extremity lean mass, eccentric strength of the quadriceps, and energy absorption about the knee during landing in women, but not in men. The investigators concluded that the sex difference in strength may contribute to the underlying mechanisms of the sex difference in correlation between strength and energy absorption. In this study, the findings of significant correlations in women but not in men were consistent with these 2 studies. Secondary analysis revealed that men had greater peak force production during isometric squats compared with women. It is postulated that the lower force production at greater knee flexion angles in women led to a more important role of strength in determining their landing mechanics. However, other components such as motor control and learning of movement patterns may play an important role in affecting landing mechanics in men. Herman et al. (20) identified the importance of using feedback alongside strength training as an effective way of altering lower extremity biomechanics associated with decreased ACL loading, suggesting that both strength and the motor learning of movement patterns may affect landing mechanics.

Correlations between the force production and knee flexion angles during landing in women were stronger for isometric squats at greater knee flexion angles (55, 70, and 90°) compared with the smallest knee flexion angle (35°). Consistent with previous literature (35,46), secondary analysis of the current results showed that the peak force production decreased as the knee flexion angle increased during isometric squats. As Figure 1 shows, the moment arms for the vertical ground reaction forces around the knee and hip are generally increased as the knee flexion angle is decreased. With the same muscle forces and joint moments, an increased moment arm of vertical ground reaction force will result in a decreased magnitude of vertical ground reaction force. Therefore, as the knee flexion angle is increased, the lower leg musculature is placed in a position with decreased mechanical advantage for producing vertical ground reaction force. During the jump-landing-jump task, in which the performance goal was to reach maximum jump height, individuals with greater strength at deep knee flexion may have greater knee flexion angles during landing because it may allow them to use the force generated at that knee angle for a maximum jump. However, individuals who are weaker at deep knee flexion may try to avoid deep knee flexion, which may compromise their ability to produce force for a maximum jump. Therefore, it is reasonable to observe stronger correlations for the peak force production during isometric squats at greater knee flexion. In this study, it was postulated that the choice of peak knee flexion angles in women was for the preparation of the jumping phase and affected by the strength at deep knee flexion angles. At the meantime, these participants who planned to land with decreased peak knee flexion angles still needed to absorb the kinetic energy of the body during the landing phase. It seemed that they also chose to decrease their knee flexion angles at initial contact to allow a certain joint range of motion to absorb impact forces during landing. This proposed mechanism may explain why strength at deep knee flexion angles correlated with both knee flexion angles at initial contact and peak knee flexion angles during landing in women.

Several limitations exist in this study. First, a regression approach was used to predict peak force production during isometric squats at certain knee flexion angles because of relatively large variability in actual knee flexion angles during each isometric squat condition. A better control of calibration trials, participants' movements, and actual knee flexion angles during isometric squat may avoid the errors introduced by the regression approach. Second, although most participants had performed squats as a strength training exercise, the current investigators did not control or quantify participants' experience in performing squats nor their preferred forms or techniques during squats. Participants' experience in certain squat positions may be a contributing factor to the force production. Future studies may quantify how different components such as squat experience, forms and techniques, lean mass, and muscle activation affect the force production during isometric squats. This information will be important for developing training strategies for women to increase their force production during isometric squats. Third, despite using an isometric squat test and a range of knee flexion angles being an improvement on the open-chain exercises, it may still not be fully representative of the dynamic strength required to perform a drop jump landing. Muscle action required during jump landing is mainly eccentric and concentric, and the muscle action tested in this study was isometric. Future studies should develop a more dynamic test that could better represent the dynamic strength of a drop jump landing such as isokinetic testing of the force production of the lower extremity at different joint angles during a simulated squat task. Fourth, the findings of this study were limited to correlational analysis. Future studies may increase the sample size and compare isometric strength among groups with different knee flexion angles during landing (low risk vs. moderate risk vs. high risk). In addition, the findings of this study should not be generalized to a cause-effect relationship.

PRACTICAL APPLICATIONS

The findings of this study indicate that posture-specific strength training may be considered as a component of intervention to increase knee flexion angles during landing in women. Previously, investigators have shown that individuals could increase knee flexion immediately after instruction; however, decreased jump height and increased stance time were observed (13,32). Landing with greater knee flexion may impose greater demands on the lower extremity musculature. Simply increasing knee flexion angle without increasing strength at greater knee flexion is likely to decrease the efficiency of force production and result in decreased performance. Research has shown that isometric squat training at greater knee flexion angles can increase peak force production during isometric squats (46) and increase knee extension moments at greater knee flexion angles during a squat jump (41). Isometric training at specific knee flexion angles has been shown to result in shifts of peak isokinetic torque in the direction of the training knee angles (2). As such, the decreased performance associated with increased knee flexion angles during landing may overcome if the force and power production at greater knee flexion can be enhanced. Future intervention studies to identify how squat training at greater knee flexion may affect knee flexion angles and performance during landing in women are needed to confirm this speculation.

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REFERENCES

1. Agel, J, Arendt, EA, and Bershadsky, B. Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: A 13-year review. *Am J Sports Med* 33: 524–530, 2005.
2. Alegre, LM, Ferri-Morales, A, Rodriguez-Casares, R, and Aguado, X. Effects of isometric training on the knee extensor moment-angle relationship and vastus lateralis muscle architecture. *Eur J Appl Physiol* 114: 2437–2446, 2014.
3. Benjamini, Y and Hochberg, Y. Controlling the false discovery rate: A practical and powerful approach to multiple testing. *J R Stat Soc Ser B* 57: 289–300, 1995.
4. Benjaminse, A, Gokeler, A, Dowling, AV, Faigenbaum, A, Ford, KR, Hewett, TE, Onate, JA, Otten, B, and Myer, GD. Optimization of the anterior cruciate ligament injury prevention paradigm: Novel feedback techniques to enhance motor learning and reduce injury risk. *J Orthop Sports Phys Ther* 45: 170–182, 2015.
5. Beutler, A, de la Motte, S, Marshall, S, Padua, D, and Boden, B. Muscle strength and qualitative Jump-Landing differences in male and female military cadets: The jump-acl study. *J Sports Sci Med* 8: 663–671, 2009.
6. Boling, MC, Padua, DA, Marshall, SW, Guskiewicz, K, Pyne, S, and Beutler, A. A prospective investigation of biomechanical risk factors for patellofemoral pain syndrome: The joint undertaking to monitor and prevent ACL injury (JUMP-ACL) cohort. *Am J Sports Med* 37: 2108–2116, 2009.
7. Brown, DW, Taylor, KA, Utturkar, GM, Spritzer, CE, Queen, RM, Garrett, WE, and DeFrate, LE. Modification of in vivo ACL strain patterns during jump landing through verbal instruction. Presented at: Orthopaedic research Society 2012 Annual Meeting; February 5, 2012; San Francisco, CA.
8. Carcia, CR, Kivlan, B, and Scibek, JS. The relationship between lower extremity closed kinetic chain strength & sagittal plane landing kinematics in female athletes. *Int J Sports Phys Ther* 6: 1–9, 2011.
9. Cohen, J. *Statistical Power Analysis for the Behavioural Sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum Associates, 1988.
10. Dai, B, Herman, D, Liu, H, Garrett, WE, and Yu, B. Prevention of ACL injury, part I: Injury characteristics, risk factors, and loading mechanism. *Res Sports Med* 20: 180–197, 2012.
11. Dai, B, Heinbaugh, EM, Ning, X, and Zhu, Q. A resistance band increased internal hip abduction moments and gluteus medius activation during pre-landing and early-landing. *J Biomech* 47: 3674–3680, 2014.
12. Dai, B, Mao, D, Garrett, WE, and Yu, B. Anterior cruciate ligament injuries in soccer: Loading mechanisms, risk factors, and prevention programs. *J Sport Health Sci* 3: 299–306, 2014.
13. Dai, B, Garrett, WE, Gross, MT, Padua, DA, Queen, RM, and Yu, B. The effects of 2 landing techniques on knee kinematics, kinetics, and performance during stop-jump and side-cutting tasks. *Am J Sports Med* 43: 466–474, 2015.
14. Dai, B, Mao, M, Garrett, WE, and Yu, B. Biomechanical characteristics of an anterior cruciate ligament injury in javelin throwing. *J Sport Health Sci*. In press. doi: 10.1016/j.jshs.2015.07.004.
15. Devita, P and Skelly, WA. Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Med Sci Sports Exerc* 24: 108–115, 1992.
16. Donohue, MR, Ellis, SM, Heinbaugh, EM, Stephenson, ML, Zhu, Q, and Dai, B. Differences and correlations in knee and hip mechanics during single-leg landing, single-leg squat, double-leg landing, and double-leg squat tasks. *Res Sports Med*. In press. doi: 10.1080/15438627.2015.1076413.
17. Dowling, AV, Favre, J, and Andriacchi, TP. Inertial sensor-based feedback can reduce key risk metrics for anterior cruciate ligament injury during jump landings. *Am J Sports Med* 40: 1075–1083, 2012.
18. Edwards, S, Steele, JR, Cook, JL, Purdam, CR, and McGhee, DE. Lower limb movement symmetry cannot be assumed when investigating the stop-jump landing. *Med Sci Sports Exerc* 44: 1123–1130, 2012.

19. Fox, AS, Bonacci, J, McLean, SG, Spittle, M, and Saunders, N. What is normal? female lower limb kinematic profiles during athletic tasks used to examine anterior cruciate ligament injury risk: A systematic review. *Sports Med* 44: 815–832, 2014.
20. Herman, DC, Onate, JA, Weinhold, PS, Guskiewicz, KM, Garrett, WE, Yu, B, and Padua, DA. The effects of feedback with and without strength training on lower extremity biomechanics. *Am J Sports Med* 37: 1301–1308, 2009.
21. Hewett, TE, Myer, GD, Ford, KR, Heidt, RS Jr, Colosimo, AJ, McLean, SG, van den Bogert, AJ, Paterno, MV, and Succop, P. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *Am J Sports Med* 33: 492–501, 2005.
22. Hori, N, Newton, RU, Kawamori, N, McGuigan, MR, Kraemer, WJ, and Nosaka, K. Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. *J Strength Cond Res* 23: 874–882, 2009.
23. Koga, H, Nakamae, A, Shima, Y, Iwasa, J, Myklebust, G, Engebretsen, L, Bahr, R, and Krosshaug, T. Mechanisms for noncontact anterior cruciate ligament injuries: Knee joint kinematics in 10 injury situations from female team handball and basketball. *Am J Sports Med* 38: 2218–2225, 2010.
24. Krosshaug, T, Nakamae, A, Boden, BP, Engebretsen, L, Smith, G, Slauterbeck, JR, Hewett, TE, and Bahr, R. Mechanisms of anterior cruciate ligament injury in basketball: Video analysis of 39 cases. *Am J Sports Med* 35: 359–367, 2007.
25. Lephart, SM, Ferris, CM, Riemann, BL, Myers, JB, and Fu, FH. Gender differences in strength and lower extremity kinematics during landing. *Clin Orthop Relat Res* 401: 162–169, 2002.
26. Malfait, B, Sankey, S, Firhad Raja Azidin, RM, Deschamps, K, Vanrenterghem, J, Robinson, MA, Staes, F, and Verschueren, S. How reliable are lower-limb kinematics and kinetics during a drop vertical jump?. *Med Sci Sports Exerc* 46: 678–685, 2014.
27. Mather, RC III, Koenig, L, Kocher, MS, Dall, TM, Gallo, P, Scott, DJ, Bach, BR Jr, and Spindler, KP; MOON Knee Group. Societal and economic impact of anterior cruciate ligament tears. *J Bone Joint Surg Am* 95: 1751–1759, 2013.
28. Matuszak, ME, Fry, AC, Weiss, LW, Ireland, TR, and McKnight, MM. Effect of rest interval length on repeated 1 repetition maximum back squats. *J Strength Cond Res* 17: 634–637, 2003.
29. McCurdy, K, Walker, J, Saxe, J, and Woods, J. The effect of short-term resistance training on hip and knee kinematics during vertical drop jumps. *J Strength Cond Res* 26: 1257–1264, 2012.
30. Mizner, RL, Kawaguchi, JK, and Chmielewski, TL. Muscle strength in the lower extremity does not predict postinstruction improvements in the landing patterns of female athletes. *J Orthop Sports Phys Ther* 38: 353–361, 2008.
31. Montgomery, MM, Shultz, SJ, Schmitz, RJ, Wideman, L, and Henson, RA. Influence of lean body mass and strength on landing energetics. *Med Sci Sports Exerc* 44: 2376–2383, 2012.
32. Munro, A and Herrington, L. The effect of videotape augmented feedback on drop jump landing strategy: Implications for anterior cruciate ligament and patellofemoral joint injury prevention. *Knee* 21: 891–895, 2014.
33. Myer, GD, Ford, KR, McLean, SG, and Hewett, TE. The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *Am J Sports Med* 34: 445–455, 2006.
34. Padua, DA, DiStefano, LJ, Beutler, AI, de la Motte, SJ, DiStefano, MJ, and Marshall, SW. The Landing error scoring system as a Screening tool for an anterior cruciate ligament injury-prevention program in Elite-youth soccer athletes. *J Athl Train* 50: 589–595, 2015.
35. Paulus, DC, Reiser, RF II, and Troxell, WO. Pneumatic strength assessment device: Design and isometric measurement. *Biomed Sci Instrum* 40: 277–282, 2004.
36. Prodromos, CC, Han, Y, Rogowski, J, Joyce, B, and Shi, K. A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. *Arthroscopy* 23: 1320–1325.e6, 2007.
37. Read, MM and Cisar, C. The influence of varied rest interval lengths on depth jump performance. *J Strength Cond Res* 15: 279–283, 2001.
38. Schmitz, RJ and Shultz, SJ. Contribution of knee flexor and extensor strength on sex-specific energy absorption and torsional joint stiffness during drop jumping. *J Athl Train* 45: 445–452, 2010.
39. Shultz, SJ, Nguyen, AD, Leonard, MD, and Schmitz, RJ. Thigh strength and activation as predictors of knee biomechanics during a drop jump task. *Med Sci Sports Exerc* 41: 857–866, 2009.
40. Taylor, KA, Terry, ME, Utturkar, GM, Spritzer, CE, Queen, RM, Irribarra, LA, Garrett, WE, and DeFrate, LE. Measurement of in vivo anterior cruciate ligament strain during dynamic jump landing. *J Biomech* 44: 365–371, 2011.
41. Ullrich, B, Heinrich, K, Goldmann, JP, and Bruggemann, GP. Altered squat jumping mechanics after specific exercise. *Int J Sports Med* 31: 243–250, 2010.
42. Walden, M, Krosshaug, T, Bjorneboe, J, Andersen, TE, Faul, O, and Hagglund, M. Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: A systematic video analysis of 39 cases. *Br J Sports Med* 49: 1452–1460, 2015.
43. Wilson, GJ, Murphy, AJ, and Walshe, A. The specificity of strength training: The effect of posture. *Eur J Appl Physiol Occup Physiol* 73: 346–352, 1996.
44. Yu, B, Lin, CF, and Garrett, WE. Lower extremity biomechanics during the landing of a stop-jump task. *Clin Biomech (Bristol, Avon)* 21: 297–305, 2006.
45. Yu, B and Garrett, WE. Mechanisms of non-contact ACL injuries. *Br J Sports Med* 41(Suppl 1):i47–51, 2007.
46. Zatsiorsky, VM and Kraemer, WJ. *Science and Practice of Strength Training* (2nd ed.). Champaign, IL: Human Kinetics, 2006.