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ACL Injuries in the Female Athlete

Causes, Impacts, and Conditioning Programs

With DVD-ROM

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Gender Differences in Core Strength and Lower Extremity Function During the Single-Leg Squat Test

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Introduction

Anterior cruciate ligament (ACL) injury is one of the most serious and costly knee injuries sustained by female athletes [48]. It has been estimated that orthopedic surgeons perform approximately 100,000 ACL reconstructions each year in the United States [48]. Irrespective of the costs associated with diagnostic testing and rehabilitation, Lubowitz and Appleby [28] recently reported a cost per case of $12,740 for hospital and professional fees. More compelling is the fact that recent evidence has suggested that athletes who incur ACL injury have a higher probability of developing knee osteoarthritis [27, 51]. Based on these emerging data, researchers have directed much attention toward the development and implementation of ACL injury prevention programs [17, 30, 34].

Over 70 % of all ACL injuries in soccer and basketball occur via a noncontact mechanism [2]. During these sports, women commonly incur this injury when performing an open cutting maneuver which involves deceleration and sudden changes in direction on a fixed foot. During this maneuver, female athletes tend to exhibit a greater amount of knee valgus, femoral internal rotation, and tibial external rotation, collectively referred to as "dynamic knee valgus" [18, 29]. Using a cadaveric model, Fung and Zhang [15] demonstrated how dynamic knee valgus can impart excessive strain of the ACL over the lateral femoral condyle.

ACL injury etiology in the female athlete is a multifactorial problem that may result from

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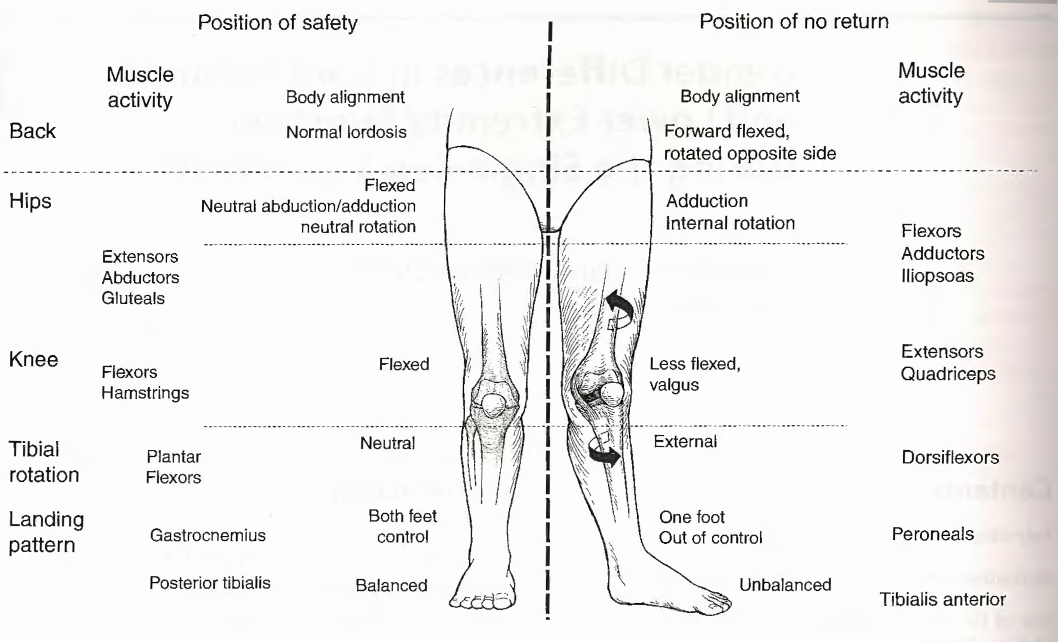

Fig. 11.1 Muscle activity and body alignment is shown for the position of safety (*left*) and "position of no return" (*right*). The position of safety occurs with knee flexed, hip flexed and neutral, and two-footed balanced landing. In contrast, the "position of no return" occurs when the body is more upright with the hips and knees less flexed, resulting in uncontrolled body rotation when landing. The muscle imbalance and position of trunk and joints place knee at risk for ACL tear

anatomical/structural, hormonal, neuromuscular, and biomechanical factors [47]. Anatomical/structural and hormonal factors may contribute to injury in women but generally are not modifiable. However, neuromuscular and biomechanical factors are amenable to change and a focus of much research. Specifically, women demonstrate lower extremity movement and muscle firing patterns that make them more susceptible to ACL injury. To explain these patterns and possible contribution to ACL injury, Ireland [20] described the "position of no return" shown in Fig. 11.1. The safe position (shown on the left) incorporates a more flexed hip and knee position which facilitates muscles of hip external rotation, abduction, lumbar spine extension, and hamstring activation to land in a safe, flexed hip, and flexed knee position. In the "position of no return" (shown on the right), the body is more upright, the back is flexed forward, the hip is in adduction/internal rotation, and the knee is less flexed which reduces the mechanical advantage of the muscles that are activated in the preferred position of safety. In the position of no return, it is hypothesized that there is an uncontrolled landing with a rapid whiplike action on a fixed pronated foot with the tibia externally rotated. Axial loading occurs when the femur whips into an internally rotated position and ACL injury occurs. According to this model, women often perform athletic maneuvers with increased trunk flexion that can reduce pelvic stability. Reduced pelvic stability in turn may cause increased hip adduction and hip internal rotation. Together, these combined motions may lead to increased knee valgus loading, making the female athlete more susceptible to injury [18].

For over 10 years, researchers have examined the interaction between hip and knee mechanics in the female athlete and reported faulty hip mechanics compared to males during landing and cutting maneuvers [11, 13, 22, 23, 35]. A limitation of these studies has been the use of expensive,

Fig. 11.2 Single-leg mini-squat done while standing on a step. (**a**) The male athlete has good balance, with hip-over-knee-over-ankle control and a level pelvis. (**b**) The female athlete has valgus at the knee, resulting from the proximal body position of femoral internal rotation and adduction, leading to subsequent tibia external rotation and pronation, in order to remain upright doing this maneuver. There is pelvic drop on contralateral side

3-dimensional (3-D) motion analysis systems that are not conducive for a clinical setting. To address this limitation, more recent works have compared 3-D lower extremity measures to frontal plane data collected using more simplistic 2-dimensional (2-D) techniques. Data from these investigations have found that examination of frontal plane movement may be a useful screening tool to identify athletes who may exhibit increased dynamic knee valgus during athletic maneuvers [32, 54].

The single-leg squat test represents a common screening tool that clinicians may use to assess frontal plane lower extremity motion. An advantage of this screening tool is that it allows the examiner to assess control and position of the trunk and entire lower extremity. For example, in normal healthy individuals, obvious differences may be seen between males and females as they perform this test. An example is shown in Fig. 11.2a, where the male exhibits proximal control as evidenced by a straight hip-over-knee-over ankle position. In contrast, the female (Fig. 11.2b) has a valgus knee position driven proximally by hip internal rotation and adduction on a fixed pronated foot with tibial external rotation. A side view shown in Fig. 11.3a shows the male demonstrating the preferred lumbar spine position, with a posteriorly rotated pelvis. However, the female (Fig. 11.3b) has a forward lumbar spine position, and the pelvis is anteriorly rotated. She exhibits less hip flexion than the male. This pelvis position drives the hip into internal rotation and adduction, potentially creating a risk position for ACL injury.

The purpose of this chapter is to examine the use of the single-leg squat as a screening tool to identify the female athlete who may be at increased risk for sustaining an ACL injury. This chapter will begin with a brief overview of the core and core stability and explain the use of the single-leg squat as a measure of core stability. The remaining sections will provide information on the association between core strength, neuromuscular activity, and lower extremity function during a single-leg squat and identify gender differences for these variables. It is our intent that the reader can use this information to identify the at-risk female who may benefit from participation in an ACL injury prevention program.

Fig. 11.3 Single-leg mini-squat shown from the side. (**a**) The male demonstrates a more posteriorly rotated pelvis, with the lumbar spine in neutral, and better balance with the knee flexed. (**b**) Female has a forward thoracic-lumbar spine movement with pelvic drop and anterior pelvis rotation

Critical Points

- As data have suggested an increased prevalence of osteoarthritis following ACL injury, attention has been directed toward identifying athletes who may be at risk for injury and may benefit from participation in an ACL injury prevention program.
- ACL injury etiology is a multifactorial knee problem that is likely influenced by core function.
- The single-leg squat is a clinically useful tool for identifying faulty movements of the core and lower extremity that may make an athlete susceptible to ACL injury.

Definition and Principles of Core Stability

Anatomically, the core may be defined as the lumbopelvic-hip complex which includes the trunk, thoracic-lumbar spine, pelvis, hip joints, and all ligamentous and muscular components associated with them. Stability is the ability of a system to resist change. Pope and Panjabi [41] defined a stable object as one in an "optimal" state of equilibrium. Core stability is achieved when the lumbopelvic-hip complex resists change to create an optimal state of equilibrium.

To obtain an optimal state of core equilibrium, a complex coordination of many passive and active elements must occur. Bony architecture and soft tissue compliance contribute to passive stability, and muscle contraction provides the active component of stability [52]. The active component may provide stability through increased abdominal pressure, spinal compressive forces, and trunk and hip muscle stiffness [52]. If one or more of these restraints are damaged or weakened, the core may be in suboptimal equilibrium. Therefore, the maintenance of lumbopelvic-hip complex stability requires a highly coordinated interaction of the spine and hip musculature to provide trunk and hip stiffness.

Stability of the spine is one key component of core equilibrium. Due to the spine's inherent unstable nature, coordination of muscular and neural elements is necessary [38]. Cholewicki and VanVliet [6] examined spinal stability and reported that no muscle contributed >30 % to overall stability.

Activation of trunk musculature provides a stable platform for lower extremity movement. Hodges and Richardson [19] examined trunk musculature onset during lower extremity movement. Their findings highlighted the importance of abdominal contraction, specifically, the transverse abdominis and the multifidus, in advance of lower extremity movement. They concluded that co-contraction of these antagonist muscle groups increased intra-abdominal pressure to facilitate spinal stiffness [52]. Maintenance of core stability occurs when spine stability and trunk musculature activation is in synchrony.

Hip stability also contributes to core stability, as well as dynamic lower extremity alignment. The gluteus medius, gluteus minimus, and upper fibers of the gluteus maximus provide stability in the frontal plane [36]. Together, these muscles work to maintain the pelvis in a level position during single-leg weight-bearing activities. Due to the triplanar orientation of its fibers, the gluteus maximus affords additional stabilization via its ability to control hip internal rotation [43]. The hip external rotators also may play a significant role in stability and injury prevention. Souza and Powers [50] found that hip extensor weakness was a predictor of increased hip internal rotation during running in females with anterior knee pain. Leetun et al. [25] assessed trunk and hip strength in basketball and track athletes prior to their competitive seasons. They then prospectively followed these athletes to determine those that subsequently sustained a lower extremity injury. Of all muscle performance measures taken, only strength of the short hip external rotators (e.g., piriformis, quadratus femoris, obturator internus, superior gemellus, and inferior gemellus) was deemed important for predicting athletes who ultimately incurred a lower extremity injury.

In summary, an emerging body of evidence has provided important information regarding the role of the core on lower extremity function. However, most investigations have been conducted in a laboratory setting not conducive for everyday clinical assessment. The single-leg squat is a clinical tool that can be helpful for assessing the influence of the core on lower extremity function during dynamic movement. The remaining sections provide additional information for the use of this assessment tool.

Critical Points

- Core stability can be defined as the ability of the lumbopelvic-hip complex to resist change and maintain an optimal state of equilibrium.
- A highly coordinated interaction of active and passive elements is necessary to provide a base for lower extremity movements.
- Co-contraction of abdominal and spinal musculature contributes to core stability by increasing intra-abdominal pressure and spinal stiffness.
- Hip musculature provides stability by maintaining a level pelvis and controlling femoral rotation.

Use of the Single-Leg Squat as a Measure of Core Stability

Since core stability involves the interaction of many complex elements, clinical measures are difficult. The ideal test is one that is reliable, valid, and easily administered in a busy clinical setting. The single-leg squat is one such test that does not require any devices other than an examiner. The test is typically performed with the patient standing on the floor or on a foot stool in front of the examiner. The patient is instructed to stand on one lower extremity, squat to a desired level of knee flexion (usually 90°), and then return to the starting position. There are no instructions given for the position of the hands; they may either be placed on the hips or left hanging free. The examiner notes the patient's overall trunk control as well as the position of the hip, knee, and foot. Although various descriptions of the test exist, all focus on trunk and lower extremity control and position [1, 46, 53, 57]. The most common variation between tests has been the squat depth.

The goal of the single-leg squat test is to identify the athlete who may have weakness of the core and hip musculature that may make the knee prone to injury. Increased hip adduction and internal rotation during the single-leg squat suggest poor hip muscular control and greater reliance on quadriceps activity for knee control [57]. Increased quadriceps activity, especially with the knee in minimally flexed position, can cause increased anterior tibial translation and strain on the ACL [4, 31].

The usefulness of any clinical tool depends on its reliability and validity. Munro et al. [33] examined the reliability of using the frontal plane projection angle (FPPA) as described by Willson et al. [53] to measure dynamic knee valgus during a single-leg squat. For this purpose, subjects were instructed to squat down as far as possible (to a minimum of 45° knee flexion). At the point of the greatest knee flexion angle, the investigators measured the FPPA. The FPPA was formed by drawing one line from the middle of the proximal femur to the middle of the tibiofemoral joint and a second line between the middle of the tibiofemoral joint and the ankle mortise (Fig. 11.4). These investigators reported between-day intraclass correlation coefficients of 0.88 and 0.72 for males and females, respectively.

Ageberg et al. [1] determined the reliability and validity of a similar single-leg squat test. Instead of measuring the FPPA, these researchers used a dichotomous rating system to quantify frontal plane knee motion. For this purpose, two experienced clinicians rated subjects as having either a "knee-over-foot" or a "knee-medial-to-foot" position when performing a single-leg squat to maximum knee flexion. All subjects performed five trials of the test at a standardized rate (20 squats/min). Subjects rated as having a "knee-over-foot" position performed at least three of the five trials with the knee aligned over or lateral to the second toe. Those who performed at least three of the five trials with the knee aligned medial to the second toe were classified as having a "knee-medial-to-foot" position. This method had excellent between-rater reliability as evidenced by a kappa value of 0.92 and a 96 % agreement.

To establish validity of the single-leg squat test, Ageberg et al. [1] concurrently collected 3-D motion analysis data. Findings from the 2-D analysis showed that the subjects who received a "knee-medial-to-foot" rating exhibited a greater

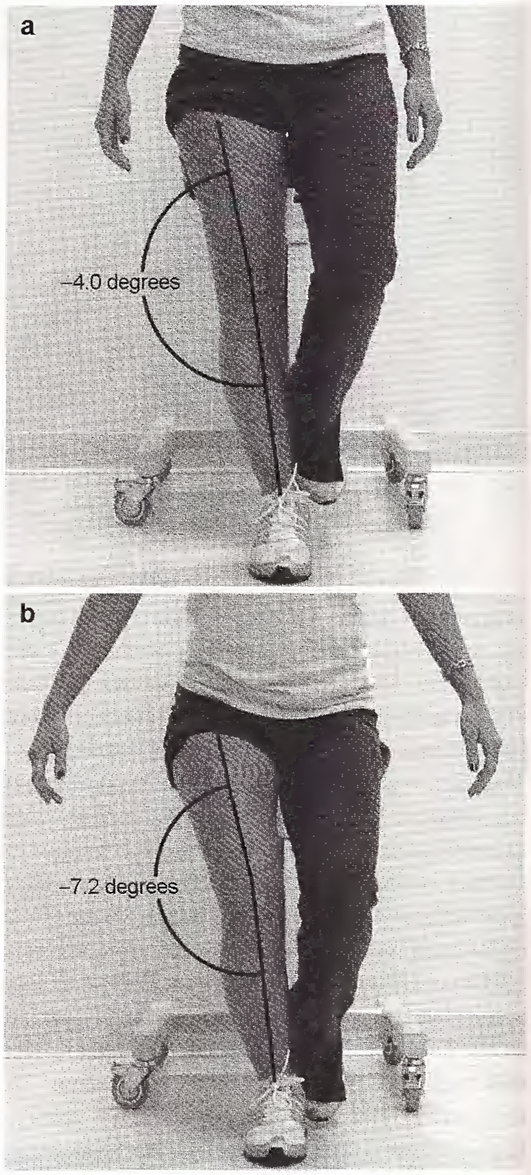

Fig. 11.4 The measurement of the frontal plane projection angles doing a single-leg stance (**a**) and single-leg squat (**b**). The angle is measured between two lines, the midpoint of the knee joint to midpoint of the ankle mortise and on the anterior superior iliac spine to the midpoint of knee joint. Reproducible measurements can be documented with a camera during positions of knee flexion and normalized based on height of the subject, with knee flexion controlled by the stool height behind the subject as shown. (Reprinted with permission from Willson et al. [53])

peak thigh angle (in relation to the horizontal plane) that was more medially orientated relative to the knee. This orientation suggested that these subjects completed the single-leg squat with the knee in a more valgus position. Furthermore, data from the 3-D analysis revealed greater hip internal rotation in these same subjects. In summary, motion analysis data confirmed the ability of the observers to identify subjects who performed the test with a less than optimal hip position.

Due to its simplicity, reliability, and validity, the single-leg squat test is useful for evaluating female athletes who might be at risk for sustaining an ACL injury. The next section will highlight the association between core strength, neuromuscular activity, and lower extremity function. Understanding these interactions may assist the clinician with identifying impairments that could place an athlete at risk for sustaining a knee injury.

Critical Points

- The single-leg squat is an easy clinical test with established reliability and validity.
- It is recommended that the reader refer to the primary resources to ensure appropriate test administration and data interpretation.

Association Between Core Strength, Neuromuscular Activity, and Lower Extremity Function During a Single-Leg Squat

The main purpose of the single-leg squat assessment is to provide information regarding overall trunk and lower extremity strength, neuromuscular control, and quality of movement. When using this assessment tool, the clinician looks for the following:

- Erect trunk
- Minimal hip flexion
- Level pelvis (frontal plane)
- Abducted and externally rotated hip
- Knee over second toe position

Together, this posture suggests the athlete's ability to maintain good trunk, pelvis, and hip position during a dynamic movement.

Core Strength and Lower Extremity Function

Willson et al. [53] were one of the first investigators to examine the association between trunk, hip, and knee isometric strength and the knee FPPA during a single-leg squat. They reported a significant correlation between increased trunk extension ($r=0.26$; $P=0.05$), trunk lateral flexion ($r=0.27$; $P=0.04$), hip external rotation ($r=0.40$; $P=0.004$), and a neutral FPPA (an angle closer to 0°). Although not significant, a trend existed for the importance of the hip abductors ($r=0.23$; $P=0.07$). Regarding knee strength, the investigators reported a significant correlation between the knee flexors ($r=0.33$; $P=0.02$), but not the knee extensors ($r=0.23$; $P=0.12$), and the FPPA. Although the knee flexors (hamstrings) function primarily as a knee flexor, it is noteworthy that the hamstrings also assist with hip extension. This orientation may account for the significant association found between the knee flexors and FPPA.

Using an isokinetic dynamometer to measure hip and knee strength, Claiborne et al. [7] reported a significant negative correlation between concentric peak hip abductor ($r=-0.37$; $P<0.05$), knee flexor ($r=-0.43$; $P<0.001$), and knee extensor ($r=-0.37$; $P<0.05$) torque and knee valgus during a single-leg squat. Furthermore, these three variables were significant predictors of the amount of knee valgus during a single-leg squat. It is noteworthy that these findings identified knee strength as a significant factor. Although the core and hip can help stabilize the knee, this investigation highlighted the importance of the knee muscles. Subsequent works have examined trunk and hip muscle function and single-leg squat performance and reported similar findings (Table 11.1).

Although both Willson et al. [53] and Claiborne et al. [7] reported significant associations between isometric strength measures and concentric peak torque and knee valgus during a single-leg squat, correlation coefficients were considered weak to moderate at best [42]. A possible reason for these correlations might have been that these strength measures did not reflect muscle function during this dynamic task. As described above, the hip abductors and external

Table 11.1 Summary of findings from additional studies that have examined the influence of trunk and hip muscle strength on single-leg squat performance

Study	Muscle groups assessed	Single-leg squat performance rating	Relevant findings
Baldon et al. [3]	Hip abductors	3-dimensional motion analysis of pelvis, femur, and knee	Moderate negative correlation between eccentric hip abductor torque and femur and knee adduction
	Hip external rotators		Moderate negative correlation between eccentric hip external rotator torque and femur adduction
			Moderate positive correlation between eccentric hip external rotator torque and contralateral pelvic elevation and knee adduction
Crossley et al. [9]	Hip abductors Hip external rotators Trunk lateral flexors	Consensus panel of five experienced clinicians who used established criteria to rate single-leg squat performance as "good," "fair," or "poor"	Subjects who demonstrated "good" performance generated greater hip abductor and trunk lateral flexor torque
Willy and Davis [55]	Hip abductors	3-dimensional motion analysis of the pelvis, femur, and knee	Following training, subjects generated greater hip abductor and external rotator torque
	Hip external rotators		Subjects in the training group also demonstrated less hip adduction, less hip internal rotation, and greater contralateral pelvic elevation during a single-leg squat
			Controls exhibited no changes in strength or single-leg squat performance

rotators work synergistically in an eccentric manner to control hip adduction, hip internal rotation, and contralateral pelvic drop during weight-bearing activities [36].

To account for this type of muscle demand, Baldon et al. [3] examined the relationship between eccentric hip abductor and external rotator peak torque and lower extremity kinematics during a single-leg squat in males and females. Regarding eccentric hip abduction, a significant association existed between hip abductor torque and hip adduction ($r = -0.55$; $P < 0.001$) and hip abductor torque and knee varus ($r = 0.49$; $P = 0.004$). No significant correlation existed between hip abductor torque and hip internal rotation. When analyzed by gender, greater associations existed for females. Results from this analysis revealed correlations between hip abductor torque and hip adduction ($r = -0.52$; $P = 0.03$), hip internal rotation ($r = -0.47$; $P = 0.04$), and knee varus ($r = 0.61$; $P = 0.01$) for females.

For eccentric hip external rotation, the only significant correlations were between hip external rotator torque and hip adduction ($r = -0.47$; $P = 0.006$) and knee varus ($r = 0.36$; $P = 0.04$). No significant correlations existed when analyzing data for males and females separately. It is noteworthy that correlation coefficients were relatively higher between eccentric hip abductor torque and knee valgus than those reported by prior works [7, 53]. Therefore, additional investigations should continue to examine eccentric strength because it better emulates the demands placed on the hip during weight-bearing activities.

Recent works have correlated eccentric contractions of muscle fatigue on lower extremity kinematics by examining the effect of hip muscle fatigue on lower extremity kinematics during a single-leg landing. While some studies [21, 22] have reported altered kinematics following a fatigue protocol, others [16, 39] have not shown this effect. As investigators have not examined this effect during a single-leg squat, future studies are needed to better understand this influence.

In summary, evidence to date supports the influence of trunk and hip muscle function on the dynamics of lower extremity movement during a single-leg squat. These findings suggest that the trunk extensors and lateral flexors, along with the hip abductors, may stiffen the core and stabilize the pelvis. The hip external rotators may optimize knee position by minimizing the degree of hip internal rotation. More important, Zazulak et al. [56] assessed trunk control in a group of collegiate athletes and prospectively followed them to determine which athletes incurred a knee injury. They identified decreased trunk control as a significant risk factor for knee injury, especially for the female athlete. As discussed earlier, Leetun et al. [25] also prospectively followed athletes over a competitive season. They reported that athletes with less hip external rotator and hip abductor strength were more likely to sustain a lower extremity injury. Finally, preliminary data have shown improvement in single-leg squat performance in females with evident hip weakness who participated in a 6-week training program comprised of hip strengthening exercise and movement education [55]. Section "Gender Differences During a Single-Leg Squat" provides additional data with respect to gender differences in core strength and lower extremity function during a single-leg squat.

Core Neuromuscular Activity and Lower Extremity Function

Zeller and colleagues [57] were the first to compare electromyographic (EMG) activity (Table 11.2) and trunk and lower extremity kinematics (Table 11.3) between males and females during a single-leg squat. Overall, females generated greater muscle activation than males for all muscles. Furthermore, females exhibited lower extremity movement patterns indicative of less than optimal trunk, hip, and knee control. For example, males demonstrated similar trunk flexion, but 2.7 times greater trunk lateral flexion, as females. They also exhibited 1.5 times greater hip extension, whereas females had 1.2 times greater hip adduction. Together, these comparisons showed that males performed the single-leg squat task with the trunk, pelvis, and hip positioned in a more neutral manner. Furthermore, females completed the task with knee valgus 1.5 times greater than males.

Table 11.2 A comparison of mean (standard deviation) muscle amplitudes, expressed as a percent of a maximal voluntary isometric contraction, between males and females during a single-leg squat [57]

Muscle group	Males	Females
Trunk		
Rectus abdominis	22.9 (41.0)	8.5 (9.0)
Erector spinae	39.8 (7.6)	45.5 (29.8)
Hip		
Gluteus maximus	74.5 (58.7)	97.9 (38.2)
Gluteus medius	78.5 (81.8)	97.9 (38.2)
Knee		
Rectus femoris	34.3 (16.4)	78.8 (26.1)
Vastus lateralis	89.4 (48.1)	164.6 (100.1)
Biceps femoris	24.8 (18.9)	143.0 (351.5)

Table 11.3 A comparison of mean (standard deviation) maximum range of motion, expressed in degrees, for the trunk, hip, and knee between males and females during a single-leg squat [57]

Motion	Males	Females
Trunk		
Flexion	30.5 (13.7)	29.5 (10.1)
Lateral flexion	26.4 (20.1)	9.8 (9.1)
Hip		
Flexion	60.0 (8.1)	69.1 (8.4)
Extension	12.5 (5.6)	8.5 (5.7)
Adduction	14.6 (5.4)	17.8 (6.3)
Knee		
Flexion	89.5 (6.2)	95.4 (6.2)
Varus	14.4 (13.1)	6.4 (8.5)
Valgus	5.1 (4.9)	7.0 (7.0)

Important patterns of trunk, hip, and knee muscle activity also existed. Males generated 2.7 times greater rectus abdominis activity but relatively similar erector spinae activity as females. These values inferred better abdominal activation that may have allowed males to maintain a more upright and symmetrical trunk position. Furthermore, females generated 1.3 times greater gluteus maximus and medius activity, two times greater quadriceps activity, and over six times greater biceps femoris activity. This pattern may have reflected the need for greater hip and knee muscle activation to compensate for less co-activation between the trunk flexors and extensors. Together, these findings suggested the following:

- Males maintained an upright and symmetrical trunk position and exhibited a better balance between erector spinae and rectus abdominis muscle activity.
- Females completed the task with more hip adduction and knee valgus and required greater muscle activity to compete the task. Increased muscle activity most likely reflected increased neural drive compared to males to maintain hip and knee position [5, 37, 49].
- When examined simultaneously, males demonstrated better co-activation between the trunk and hip muscles that resulted in a more optimal trunk, hip, and knee position during the single-leg squat.

In summary, findings from Zeller et al. [57] support the "position of no return" [20] for explaining the influence of faulty trunk and hip function on the knee. Subjects who maintained the trunk and hip in a more neutral position and generated more symmetrical trunk and hip muscle activity performed the single-leg squat with the knee in less valgus.

Crossley et al. [9] also examined hip abductor performance during a single-leg squat (Table 11.1). They reported that subjects who performed this task with good control generated greater hip abductor and lateral trunk flexor torque during isometric strength testing. These investigators also examined gluteus medius activation during a step-up maneuver. Results from this aspect of the study showed that subjects who demonstrated greater lower extremity control during the single-leg squat also had earlier activation (onset) of the gluteus medius during the step-up task. Crossley's data suggested that subjects who performed poorly on a single-leg squat test not only exhibited diminished hip and trunk strength but also delayed gluteus medius onset during a stepping task. This delayed muscle activation may hinder pelvic and hip stability during dynamic activities.

Nguyen et al. [37] also investigated the interactions between hip muscle activation and lower extremity joint excursion during a single-leg squat. In contrast to Zeller et al. [57], Nguyen et al. assessed isometric hip extensor and hip abductor strength, as well as gluteus maximus and gluteus medius activity during this test. They reported decreased peak gluteus maximus activity as a predictor of increased hip internal rotation excursion. Conversely, increased peak gluteus maximus activity was a predictor of knee valgus excursion. They surmised that different hip activation strategies may exist for controlling hip motion compared to knee motion. These findings were consistent with Zeller et al. [57] who also reported greater knee valgus range of motion in subjects who generated greater gluteus maximus activity during the single-leg squat.

Interestingly, peak gluteus medius activity was not included in the final predictive models for either increased hip internal rotation excursion or knee valgus excursion. Powers [43] has advocated the importance of gluteus maximus function due to its ability to resist hip flexion, hip adduction, and hip internal rotation. These muscle actions may explain why the final predictive model included gluteus maximus, and not gluteus medius, activity as a predictor of knee valgus.

Regarding associations between strength and muscle activity, Nguyen et al. [37] reported a negative correlation between hip abductor torque and gluteus medius activity ($r = -0.27$; $P = 0.03$), as well as hip extensor torque and gluteus maximus activity ($r = -0.61$; $P < 0.001$). These findings agree with prior works regarding increased neural drive required to complete a functional task in subjects with evident hip weakness [5, 49].

Core Engagement and Lower Extremity Function

To our knowledge, Shirey et al. [46] were the first to examine the influence of volitional core engagement on lower extremity function during a single-leg squat in 14 females. Initially, core strength was determined using methods described by Sahrmann [45] and then, based on subjects' scores, was assigned into either a low or high core strength group. Next, these investigators collected frontal plane kinematic data during a single-leg squat under two conditions: no volitional core activation and volitional core activation (e.g., "engage the abdominal muscles" as instructed during initial core strength testing). Findings from this investigation showed reduced medial-lateral hip movement during volitional core activation for all subjects, regardless of the core strength score. Moreover, subjects with low core strength scores demonstrated less medial-lateral knee stability than those with higher core scores, irrespective of core engagement. Shirey et al. concluded that subjects with low core scores may benefit from additional training. Together, these results implied that core training may improve lower extremity performance during a single-leg squat. Additional investigations are needed to determine if a similar effect will occur during more dynamic activities.

Critical Points

- Core strength influences the quality of lower extremity kinematics during a single-leg squat.
- Individuals with good quadriceps strength demonstrate less knee valgus during a single-leg squat.
- EMG data have suggested that similar activation levels between the trunk flexors and trunk extensors, as well as the gluteus maximus and gluteus medius, can

positively affect trunk and lower extremity kinematics during a single-leg squat.
- An inverse relationship between muscle strength and EMG activity during a single-leg squat reflects an increased neural drive necessary for individuals with less strength.
- Volitional activation of the core musculature may enhance lower extremity function during a single-leg squat.

Gender Differences During a Single-Leg Squat

To date, most studies [8, 11, 12, 14, 18, 24, 26, 29] have examined gender differences during running, cutting, and drop-landing tasks, with limited data available with respect to the single-leg squat test. Sections "Core Strength and Lower Extremity Function" and "Core Neuromuscular Activity and Lower Extremity Function" provided an overview of the interrelationship between core strength, neuromuscular activity, and lower extremity function during a single-leg squat. While these sections briefly addressed gender differences, the purpose of this section is to compile the available evidence presented above in a manner to identify gender differences during a single-leg squat. It is our intent that the clinician may use this information to better identify core impairments that may make the female athlete more susceptible to ACL injury.

Zeller et al. [57] were the first to specifically examine EMG activity (Table 11.2) and kinematics (Table 11.3) between males and females during a single-leg squat. Findings from this study showed that males demonstrated better co-contraction of the trunk and hip muscles that resulted in a more vertical trunk position in combination with less hip adduction and knee valgus. This pattern suggested that symmetrical muscle co-contraction between the trunk and hip muscles could have stabilized the core to promote controlled lower extremity movement [6, 19]. Zazulak et al. [56] also reported poor trunk neuromuscular control as a predictor of lower extremity injury in the female athlete. A limitation of Zeller et al. study was the omission of core strength measures. Therefore, it remained elusive the extent that core strength might have had on lower extremity kinematics.

Willson et al. [53] compared isometric strength and the FPPA during a single-leg squat in 22 male and 22 female athletes. Clinically important associations existed for trunk lateral flexor, trunk extensor, hip abductor, hip external rotator, and knee flexor isometric strength and the FPPA when examining data combined for all subjects. When comparing strength and FPPA measures between genders, males exhibited greater isometric strength for all trunk and hip muscles except the trunk extensors. Males also tended to move toward a more neutral knee position during the single-leg squat. Conversely, females had less trunk and hip isometric strength and higher FPPA values. Unlike males, they moved toward a more valgus knee position.

In a subsequent investigation, Baldon et al. [3] found similar gender differences with respect to knee movement during a single-leg squat. As in Willson et al. study [53], women generated significantly less eccentric hip abductor and external rotator torque than men during strength testing. Females also exhibited greater contralateral pelvic drop excursion ($4.80 \pm 2.37°$ vs. $2.43 \pm 2.07°$) and greater hip adduction excursion ($4.16 \pm 2.97°$ vs. $0.01 \pm 2.63°$) than males. These excursions were accompanied with females moving into a greater amount of knee valgus than males ($4.73 \pm 4.84°$ and $0.33 \pm 3.48°$, respectively).

As discussed in section "Core Strength and Lower Extremity Function," Baldon et al. [3] determined correlations between eccentric hip abductor strength and lower limb kinematics using data compiled for all subjects and then based on gender. Correlation coefficients using only data for female subjects showed significant negative correlations between peak abductor torque and hip adduction and hip internal rotation and a significant positive correlation between hip abductor torque and knee varus. However, no significant correlations existed when analyzing these same variables for males. This finding suggested that females may rely more on hip muscle function to control frontal plane knee movement. Therefore, the single-leg squat test may be more applicable for the assessment of female athletes.

Critical Points

- Females exhibit trunk and hip weakness that can lead to greater hip adduction, hip internal rotation, contralateral pelvic drop, and knee valgus than males during a single-leg squat.
- Females generate greater hip and knee muscle EMG activity during a single-leg squat that suggests a greater reliance on the hip and knee muscles for lower extremity control.
- Stronger correlations exist between hip abductor strength and lower extremity kinematics for females than males.

Clinical Implications

ACL injury is one of the most serious knee injuries incurred by the female athlete. Attention has focused on identifying the at-risk athlete, as well as developing and implementing prevention programs. A common theme of these programs has been to minimize knee valgus during dynamic activities by focusing on exercise designed to improve strength and neuromuscular control of not only the knee but also the core [34, 40].

Most prior works have used expensive equipment in a formal laboratory setting to determine that females perform dynamic activities with altered lower extremity kinematics, making them more vulnerable to a noncontact ACL injury. Based on the current available evidence, the single-leg squat represents a clinically useful tool capable of identifying increased knee valgus during dynamic movement. The quality of lower extremity movement during a single-leg squat can provide the clinician with important inferences regarding muscle function. This information is important as it will improve the clinician's ability to develop and implement treatment strategies that target a given athlete's impairments [9].

As outlined in the beginning of section "Core Neuromuscular Activity and Lower Extremity Function," optimal posture during the single-leg squat is a vertical trunk, level pelvis, externally rotated and abducted hip, and neutral knee position. However, the examiner should be aware of possible compensatory strategies. Although excessive contralateral pelvic drop indicates hip abductor weakness, athletes can compensate for this weakness through increased trunk lean over the stance limb. While this compensation essentially minimizes the amount of contralateral pelvic drop, it can adversely affect knee function. This compensatory strategy shifts the body's center of mass over the stance limb, which in turn transfers ground reaction forces more lateral to the knee joint [43]. This orientation can impart an excessive knee valgus moment, which is a common factor leading to ACL injury in the female athlete [18].

The clinician should assess the female athlete's ability to perform the single-leg squat under controlled, symmetrical, and fatigued states. The effects of fatigue on single-leg squat performance and altered kinematics may not be evident until after repeated exercise. Dierks et al. [10] noted greater correlations between hip abductor strength and peak hip adduction ($r = -0.74$; $P = 0.002$) at the end of a prolonged run in subjects with anterior knee pain. Future studies are required to determine the number of repetitions of a single-leg squat necessary to identify altered hip and knee movement in the fatigue state.

In addition to the single-leg squat test, other measurements exist that demonstrate gender differences in core strength and posture. The plank test is useful and may be done by observing the athlete's position or assessing time to fatigue. As shown in Fig. 11.5, the athlete is instructed to obtain the plank position and a stick is placed posterior from head to heels. In the example shown in Fig. 11.5, the male demonstrates good ability to control his lumbar spine and pelvis, identified by the straight line from the lumbar spine which almost touches the stick. The natural position of the female is shown (middle photograph) with excessive lumbar lordosis, anterior rotation of the pelvis, and a significant distance between the stick and her spine. When the female was instructed to assume the proper plank position, she was able to do this for a

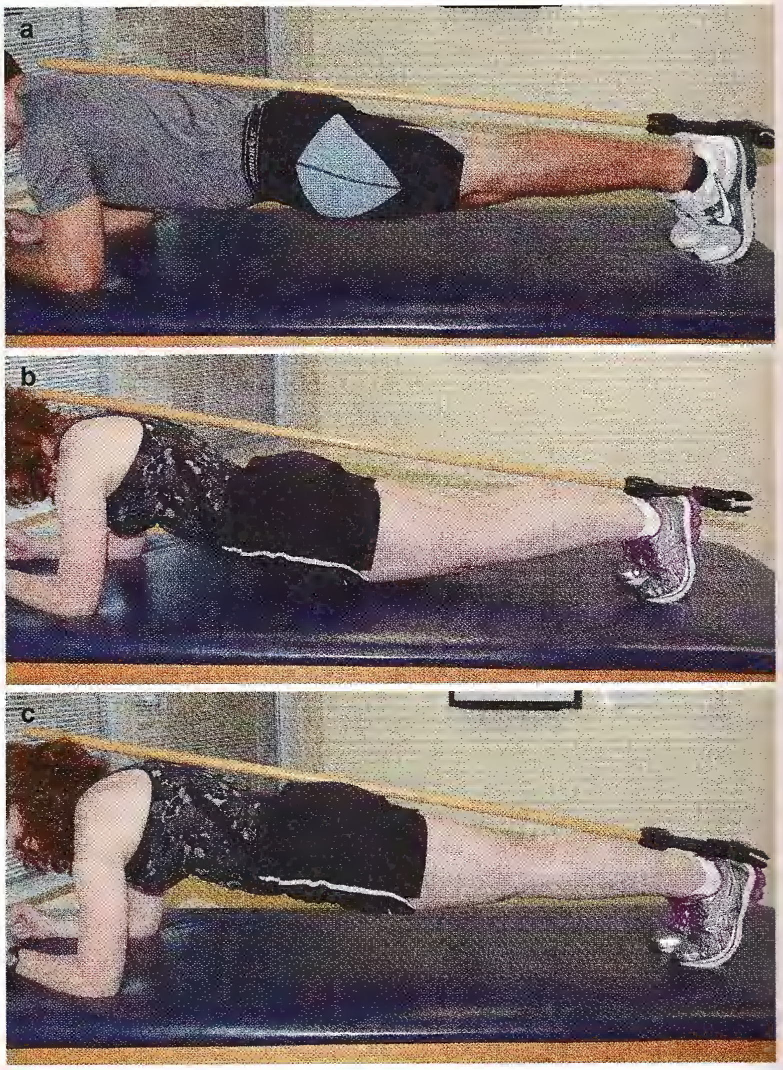

Fig. 11.5 Normal subjects performing the plank test. This test is measured by using a straight stick from the base of the skull to the feet. (**a**) The male has very little lumbar lordosis and an excellent plank position, with a posteriorly rotated pelvis and significantly greater contact with the stick than the female (**b**). (**b**) The female's plank position demonstrates excessive lumbar lordosis, forward pelvis position, and significantly less contact with the stick. (**c**) When prompted to obtain a normal plank position, the female is able to improve the position; however, there continues to be increased lumbar lordosis and anterior pelvic rotation compared to the male

short period of time as shown in the bottom photograph. Correlation of the plank test and single-leg mini-squat and drop-squat in future studies will help assess the high-risk individual and provide additions to return to play functional assessment testing.

In summary, an athlete's performance during a single-leg squat can provide clinically relevant information regarding core strength and neuromuscular activity. Together, this information can facilitate clinical decision-making for the development and implementation of ACL injury prevention programs. Figure 11.6 provides a summary of information gained during this screening test.

Critical Points

- As shown in prior works that have examined lower extremity kinematics during running, cutting, and drop-landing tasks, females exhibit greater knee valgus than males during a single-leg squat.
- Clinicians should address not only trunk and hip strength but also neuromuscular control for the female athlete who demonstrates faulty lower extremity kinematics during a single-leg squat.

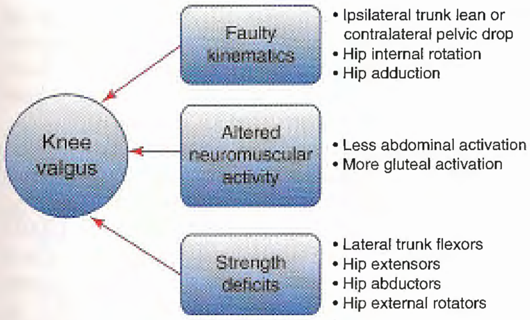

Fig. 11.6 Diagrammatic summary of factors contributing to knee valgus position. The three categories are kinematics, neuromuscular activity, and strength

Conclusion

ACL injury is one of the most serious and costly knee injuries. Seventy percent of ACL injuries occur via a noncontact mechanism, with females being at least 3.0 times more likely than males to incur injury in this manner [44]. Most data have shown that females perform demanding maneuvers with altered lower extremity mechanics that can lead to increased knee valgus loading. These findings have led to the development and implementation of prevention programs.

The success of prevention programs depends on the ability to identify the at-risk athlete using a simple, reliable, and valid screening tool. The single-leg squat represents such an assessment. Findings from the current literature have shown moderate correlations between altered trunk and hip strength and neuromuscular activity and increased knee valgus during this maneuver, especially in the female athlete. More important, researchers have seen similar faulty hip and knee mechanics in females during demanding tasks thought to make her more susceptible to ACL injury.

In summary, clinicians may use performance during a single-leg squat as an indicator of core and lower extremity function. Information gained from this assessment can help the clinician note impairments and, more importantly, prescribe individualized interventions. Therefore, we recommend the use of this assessment tool to screen females who may benefit from participation in an ACL injury prevention program.

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