13 Gender Differences in Core Strength and Lower Extremity Function During Static and Dynamic Single-Leg Squat Tests

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Abstract

This chapter discusses the principles of core strength and stability with regard to noncontact ACL injury. The single-leg squat test is described as a useful clinical tool to determine core stability. Associations between core strength, neuromuscular activity, and lower extremity function during this test are detailed. In addition, a newer dynamic single-leg squat test is described. These assessment tools are recommended to determine impairments, prescribe individualized interventions, and assess those athletes who may benefit from an ACL injury prevention training program.

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13.1 Introduction

Annually, over 200,000 anterior cruciate ligament (ACL) tears occur in the USA [1, 2]. The cost to treat these injuries each year is conservatively estimated to be $1-2 billion [3, 4]. The long-term sequelae from the initial injury may increase the economic cost well above these estimates [5]. Based on these data, scientists have sought to develop ACL injury prevention programs to mitigate the risk of injury and costs [6–8].

Up to 70% of all ACL injuries involve a noncontact mechanism [9]. Female athletes have a 2.44 greater relative risk of injury risk of sustaining an ACL tear [10]. This injury is most likely to occur when performing an open cutting maneuver that 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* [11, 12]. Using a cadaveric model, Fung and Zhang [13] demonstrated how dynamic knee valgus can impart excessive strain of the ACL over the lateral femoral condyle. The greater amount of knee valgus is thought to be a result of poor neuromuscular

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control of the hip and trunk that affects females more so than males [14-16].

ACL injury etiology in the female athlete is a multifactorial problem that may result from anatomical/structural, hormonal, neuromuscular, and biomechanical factors [17]. 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 are thus 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 [15] described the "position of no return" shown in Fig. 13.1. The safe position (shown on the left) incorporates a more flexed hip and knee position which facilitates muscles of hip external rotation and 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 abduction/ 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 support of the need for a stable and strong trunk and hip, Leetun et al. [16] reported that women who developed a lower extremity injury had weaker hip abduction and external rota-tion strength. More recently, hip external rotation weakness has been associated with ACL injury risk [18]. In addition to the hip, trunk strength and poor trunk control have also been implicated as risk factors for lower extremity injury [19-21].

For over 20 years, researchers have examined the interaction between hip and knee mechanics in the female athlete and reported faulty hip mechanics compared with males during landing and cutting maneuvers [22-26]. These studies typically employed the use of 3-dimensional

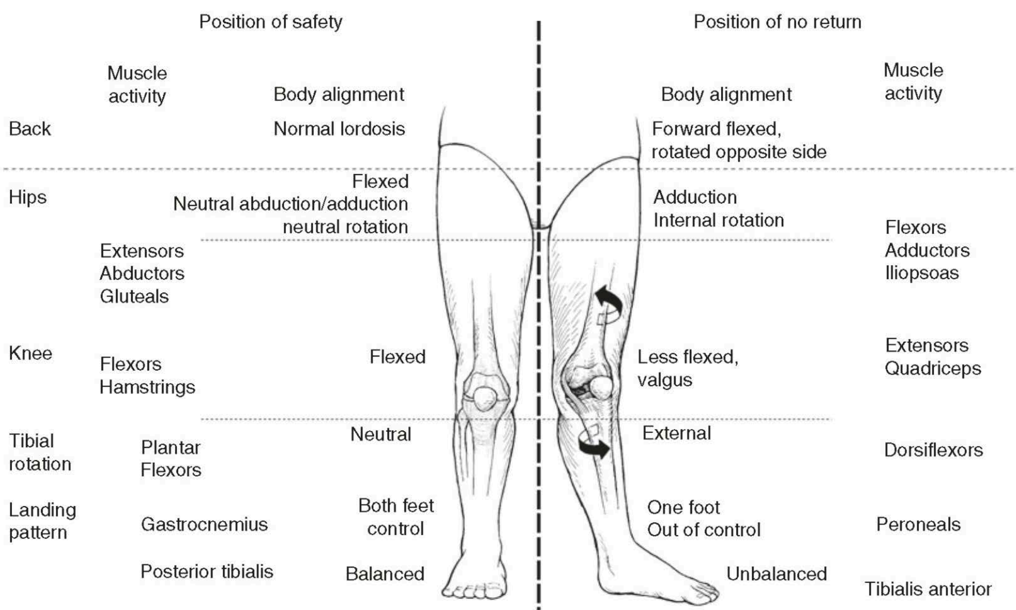

Fig. 13.1 Muscle activity and body alignment is shown for the position of safety *(left)* and "position of no return" *(right)*. The position of safety occurs with knee flexed, hip flexed and neutral, and two-footed balanced landing. In contrast, the "position of no return" occurs when the body is more upright with the hips and knees less flexed, result-ing in uncontrolled body rotation when landing. The mus-cle imbalance and position of trunk and joints places the knee at risk for ACL tear

(3-D) motion analysis systems which, although very precise, are not conducive for a clinical setting. To address this limitation, researchers have compared 3-D lower extremity hip and knee frontal plane alignment with that collected using 2-dimensional (2-D) techniques that can be replicated in the clinic. 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 [27, 28].

The single-leg squat test is 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, differences have been seen between males and females as they perform this test. An example is shown in Fig. 13.2a, where the male exhibits proximal control as evidenced by a straight hip-over-knee-over ankle position. In contrast, the female (Fig. 13.2b) 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. 13.3a shows the male demonstrating the preferred lumbar spine position, with a posteriorly rotated pelvis. However, the female (Fig. 13.3b) 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.

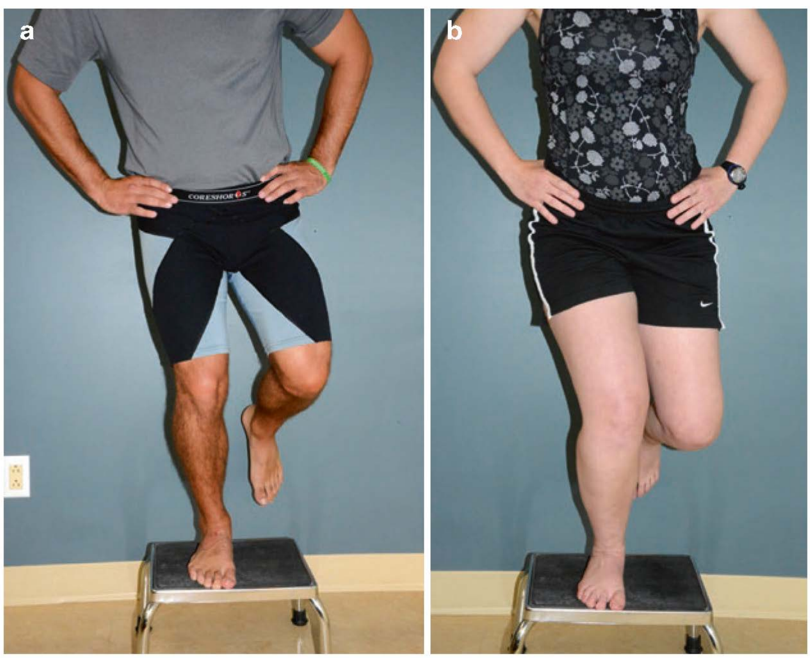

Fig. 13.2 Single-leg mini-squat, done while standing on a step. **(a)** The male athlete has good balance, with hip-over-knee-over-ankle control and a level pelvis. **(b)** The female athlete has valgus at the knee, resulting from the proximal body position of femoral internal rotation and adduction, leading to subsequent tibia external rotation and pronation, in order to remain upright doing this maneuver. There is also a pelvic drop on the side of the squat

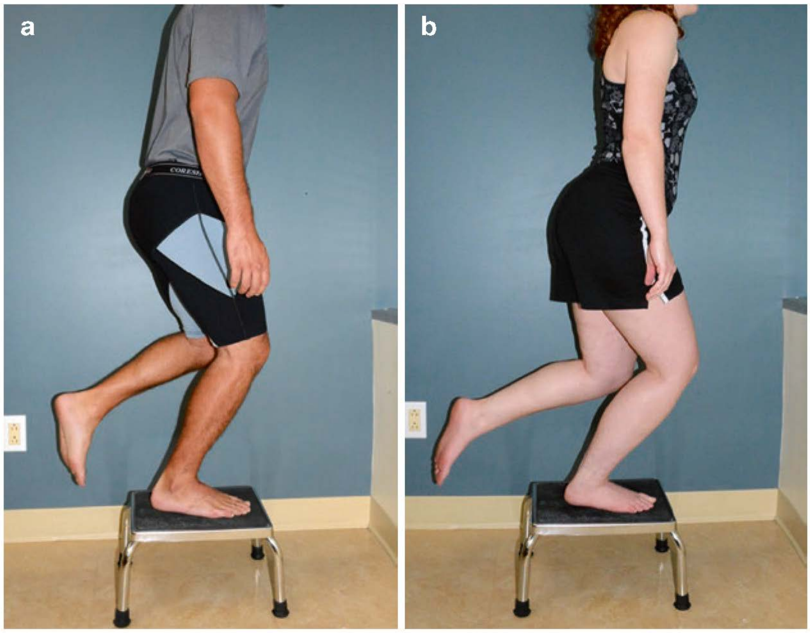

Fig. 13.3 Single-leg mini-squat shown from the side. **(a)** The male demonstrates a more posteriorly rotated pelvis, with the lumbar spine in neutral, and better balance with the knee flexed. **(b)** The female has a forward thoracic lumbar spine movement with pelvic drop and anterior pelvis rotation

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.

13.2 Definition and Principles of Core Stability

The core is 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 [29] 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 [30]. The active component provides stability through increased abdominal pressure, spinal compressive forces, and trunk and hip muscle stiffness [30]. If one or more of these restraints is 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 [31]. Cholewicki and VanVliet [32] 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 [33] examined trunk musculature onset during lower extremity movement. Their findings highlighted the importance of the transverse abdominis and the multifidus contraction, in advance of lower extremity movement. They concluded that co-contraction of these antagonist muscle groups increased intra-abdominal pressure to facilitate spinal stiffness [30]. 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 [34]. 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 [35]. The hip external rotators also may play a significant role in stability and injury prevention. Souza and Powers [36] found that hip extensor weakness was a predictor of increased hip internal rotation during running in females with anterior knee pain. Leetun et al. [16] 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.

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

Since core stability involves the interaction of many complex elements, the development of clinical measures is 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, 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 (see Sect. 13.4). Although various descriptions of the test exist, all focus on trunk and lower extremity control and position [37-40]. 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 or poor control of the core and hip musculature that 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 [40]. Increased quadriceps activity, especially with the knee in a minimally flexed position, may cause increased anterior tibial translation and strain on the ACL [41, 42].

The usefulness of any clinical tool depends on its reliability and validity. Munro et al. [43] examined the reliability of using the frontal plane projection angle (FPPA) as described by Willson et al. [39] 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. 13.4). These investigators reported between-day intraclass correlation coefficients of 0.88 and 0.72 for males and females, respectively, indicating good reliability.

Ageberg et al. [37] 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. [37] concurrently collected 3-D motion analysis data. Findings from the 2-D analysis showed that the subjects who received a

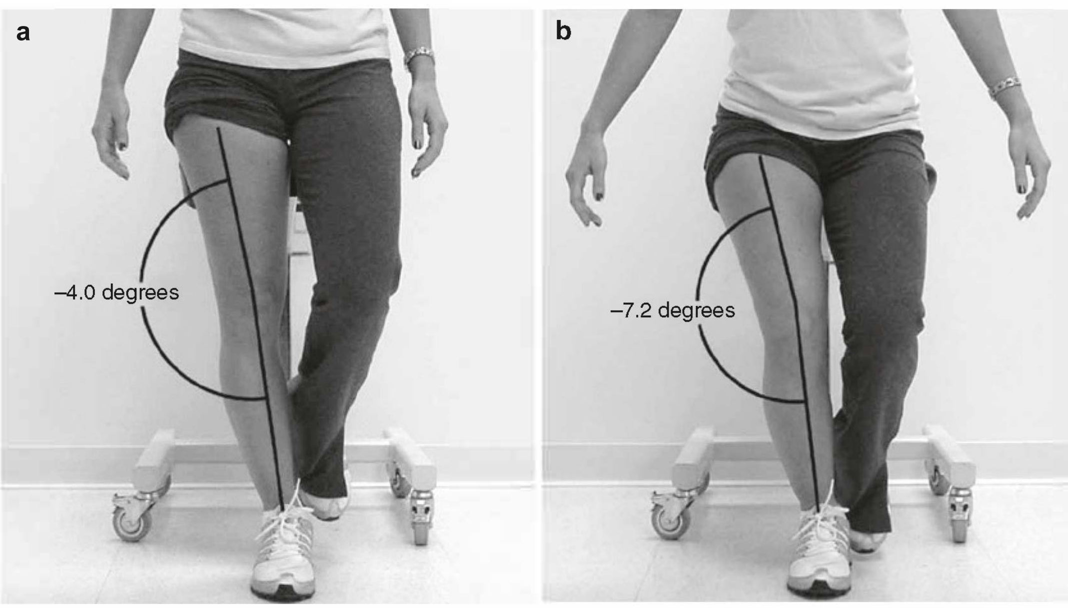

Fig. 13.4 The measurement of the frontal plane projection angles doing a single-leg stance **(a)** and single-leg squat **(b).** The angle is measured between two lines, the midpoint of the knee joint to midpoint of the ankle mortise and on the anterior superior iliac spine to the midpoint of knee joint. Reproducible measurements can be documented with a camera during positions of knee flex.ion and normalized based on height of the subject, with knee flex.ion controlled by the stool height behind the subject as shown. (Reprinted with permission from Willson et al. [39])

"knee-medial-to-foot" rating exhibited a greater peak thigh angle (in relation to the horizontal plane) that was more medially oriented 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.

13.4 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.

13.4.1 Core Strength and Lower Extremity Function

Willson et al. [39] 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. These investigators reported a significant correlation between increased trunk extensor (r = 0.26; P = 0.05), trunk lateral flexor (r = 0.27; P = 0.04), and hip external rotator (r = 0.40; P = 0.004) strength and a neutral FPPA (an angle closer to 0°). Although not significant, a trend existed for the importance of hip abductor strength (r = 0.23; P = 0.07). Regarding knee strength, the investigators reported a significant correlation between knee flexor (r = 0.33; P = 0.02), but not knee extensor (r = 0.23; P = 0.12), strength and the FPPA. Although the knee flexors (hamstrings) function primarily as a knee flexor, it was noteworthy that the hamstrings also assist with hip extension. This orientation may account for the significant association found between the knee flexors and FPPA.

Stickler et al. [44] conducted a similar study in women. This study found greater correlations between increased hip abductor (r = 0.47; P = 0.002), hip extensor (r = 0.40; P = 0.012), hip external rotator (r = 0.46; P = 0.003), and trunk lateral flexor (r = 0.43; P = 0.006) strength and a neutral FPPA. The multiple regression analysis showed that hip abductor strength accounted for 22% of the variation in FPPA. Clinically, this finding suggested that the FPPA would improve 0.2° for every 1% increase in isometric hip abductor strength (expressed as percent body mass). Such improvement may be functionally important for women with hip abductor weakness. Moreover, performance during a SLS may be more helpful for identifying strength deficits in females compared with males.

Using an isokinetic dynamometer to measure hip and knee strength, Claiborne et al. [45]

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 was 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 13.1).

Although researchers [39, 44, 45] reported significant associat10ns between isometric strength measures and concentric peak torque and knee valgus during a single-leg squat, correlation coefficients were weak to moderate at best [46]. A possible reason might have been that these strength measures did not reflect muscle function during a dynamic task. As described above, the hip abductors and external rotators work synergistically in an eccentric manner to control hip adduction, hip internal rotation, and contralateral pelvic drop during weight-bearing activities [34].

To account for this type of muscle demand, Baldon Rde et al. [47] 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 women. 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 women.

Table 13.1 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 Rde et al. [47]	• Hip abductors • Hip external rotators	3-dimensional motion analysis of pelvis, femur, and knee	• Moderate negative correlation between eccentric hip abductor torque and femur and knee adduction • Moderate negative correlation between eccentric hip external rotator torque and femur adduction • Moderate positive correlation between eccentric hip external rotator torque and contralateral pelvie elevation and knee adduction
Crossley et al. [56]	• 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 [52]	• Hip abductors • Hip external rotators	3-dimensional motion analysis of the pelvis, femur, and knee	• Following training, subjects generated greater hip abductor and external rotator torque • 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

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 was noteworthy that correlation coefficients were relatively higher between eccentric hip abductor torque and knee valgus than those reported by prior works [39, 45]. 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 also have examined the effect of hip muscle fatigue on lower extremity kinematics during a single-leg landing. While some studies [24, 48] reported altered kinematics following a fatigue protocol, others [49, 50] have not shown this effect. To date, Weeks et al. [51] are the only investigators to investigate the impact that fatigue has on single-leg squat performance. Prior to the fatigue protocol, males demonstrated significantly less peak pelvic rotation toward the stance limb, peak hip internal rotation, hip adduction range of movement, hip rotation range of movement, and medial-lateral knee motion distance (a measure of knee valgus) during a single-leg squat compared with females. No between-gender differences occurred at the trunk. After the fatigue protocol, all subjects, regardless of gender, demonstrated significant increases in peak trunk flexion, peak trunk rotation toward the stance limb, peak pelvic obliquity and rotation away from the stance limb, and increased hip adduction range of movement. However, no changes occurred with respect to the medial-lateral knee motion distance. These findings provided preliminary data on the negative impact that fatigue may have on neuromuscular control of the core. Additional studies are needed to better understand the interrelationship between muscle fatigue and single-leg squat performance.

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 importantly, Zazulak et al. [20] assessed trunk control in a group of collegiate athletes and prospectively followed them to determine which athletes incurred a knee injury. These investigators identified decreased trunk control as a significant risk factor for knee injury, especially for the female athlete. As discussed earlier, Leetun et al. [16] also prospectively followed athletes over a competitive season. 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 [52]. Section 13.5 provides additional data with respect to gender differences in core strength and lower extremity function during a single-leg squat.

13.4.2 Core Neuromuscular Activity and Lower Extremity Function

Zeller and colleagues [40] were the first to compare electromyographic (EMG) activity (Table 13.2) and trunk and lower extremity kinematics (Table 13.3) 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

Table 13.2 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 [40]

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 13.3 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 [40]

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)

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. Males 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.

hnportant 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 suggested better abdominal activation that may have allowed males to maintain a more upright and symmetrical trunk posIt10n. Furthermore, females generated 1.3 times greater gluteus maximus and medius activity, 2 times greater quadriceps activity, and over 6 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 complete the task. Increased muscle activity most likely reflected increased neural drive compared to males to maintain hip and knee position [53-55].
- 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. [40] support the "position of no return" [15] 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. [56] examined hip abductor performance during a single-leg squat (Table 13.1). This study 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. [54] investigated the interactions between hip muscle activation and lower extremity joint excursion during a single-leg squat. Decreased peak gluteus maximus activity was reported to be a predictor of increased hip internal rotation excursion. Conversely, increased peak gluteus maximus activity was a predictor of knee valgus excursion. These investigators surmised that different hip activation strategies may exist for controlling hip motion compared to knee motion.

Hollman et al. [57] compared hip abductor and extensor strength as well as gluteus medius and gluteus maximus activity during a single-leg squat in females classified as performing a single-leg squat using "good" and "poor" form. No between-group differences existed for hip abductor and extensor strength. However, there was a significant association between decreased gluteus maximus activity and increased knee valgus angle. Therefore, neuromuscular retraining, rather than strengthening exercise, may be a more important focus to decrease knee valgus during functional tasks [58, 59].

Findings from both studies [54, 57] highlighted the stabilizing effect of the gluteus maximus on knee control. Powers [35] 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 the importance of gluteus maximus, and not gluteus medius, activity on knee valgus during a single-leg squat.

13.4.3 Core Engagement and Lower Extremity Function

To our knowledge, Shirey et al. [38] were the first to examine the influence of volitional core engagement on lower extremity function during a single-leg squat in 14 females. Subjects were put into either a low or high core strength group based on scores determined using methods described by Sahrmann [60]. 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. Shirey et al. [38] 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.
- Evaluation of muscle strength based on single-leg squat performance (i.e., the degree of knee valgus) may be more meaningful for females than males.
- Volitional activation of the core musculature may enhance lower extremity function during a single-leg squat.

13.5 Gender Differences During a Single-Leg Squat

To date, most studies [11, 12, 22, 61-65] have examined gender differences during running, cutting, and drop-landing tasks, with limited data available with respect to the single-leg squat test. Sections 13.4.1 and 13.4.2 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. [40] were the first to examine EMG activity (Table 13.2) and kinematics (Table 13.3) 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 stabilizes the core to promote controlled lower extremity movement [32, 33]. Zazulak et al. [20] also reported poor trunk neuromuscular control as a predictor of lower extremity injury in the female athlete. A limitation of this 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. [39] 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 Rde et al. [47] found similar gender differences with respect to knee movement during a single-leg squat. As in the Willson et al. study [39], women generated significantly less eccentric hip abductor and external rotator torque than men during strength testing. Females also exhibited greater contralateral pelvic drop excursion ($4.80 \pm 2.37^\circ$ vs. $2.43 \pm 2.07^\circ$) and greater hip adduction excursion ($4.16 \pm 2.97^\circ$ vs. $0.01 \pm 2.63^\circ$) than males. These excursions were accompanied with females moving into a greater amount of knee valgus than males ($4.73 \pm 4.84^\circ$ and $0.33 \pm 3.48^\circ$, respectively).

As discussed in Sect. 13.4.1, Baldon Rde et al. [47] 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.

13.6 Development of a New Dynamic Single-Leg Squat Test

To date, most assessments of the single-leg step-down test performance have focused on static function. However, performance of numerous repetitions may provide additional detail into muscle function and control not captured in a static test. Recently, investigators have focused on a timed single-leg step-down test as a potential answer to this challenge. For example, Kline et al. [66] found that the number of single-leg step downs performed at 3 months post-ACL reconstruction predicted a 6-month knee biomechanics during a self-selected run. The timed single-leg step-down test proved to be a better predictor than the Y Balance Test for knee flexion excursion and the knee extensor moment.

Additionally, the timed single-leg step-down test performed as well as isometric quadriceps strength testing for the knee extensor moment and was the only predictor of knee flexion excursion. These results suggested that the timed single-leg step-down test can provide clinicians early objective data on functional performance during dynamic activities such as running.

Recently, Burnham et al. [67] investigated the relationship of hip and trunk muscle function to timed single-leg step-down function. These investigators evaluated the effect of isometric hip abduction strength, hip external rotation strength, hip extension strength, as well as plank and side plank time, on the number of single-leg step downs performed in 60 s. All tests significantly correlated with timed single-leg step-down test performance. However, only plank time was significantly predictive of the number of single-leg step downs. This study also provided important normative data; on average, healthy males performed 40 and females performed 37 single-leg step downs in 1 min. This study has helped to provide important reference values as well as insights into the relative contribution of the hip and trunk to successful performance.

Both Kline et al. [66] and Burnham et al. [67] follow similar procedures in the timed single-leg step-down test (Fig. 13.5a, b and Video 13.1). The subject stands on a 20-cm step with a digital scale (Ozeri ZB15, Ozeri USA, San Diego, CA) placed on the ground in front of the step. The stance (test) limb is positioned with the knee fully extended and the toes even with the front edge of the step. The opposite foot is held in front of the step while maintaining even height with the top of the step. Once the test begins, a single-leg step-down repetition consists of the subject flexing the stance knee, touching the scale with the left heel with $\leq$ 10% of their body weight and returning to the starting position. The number of successful repetitions completed in a 60-s period

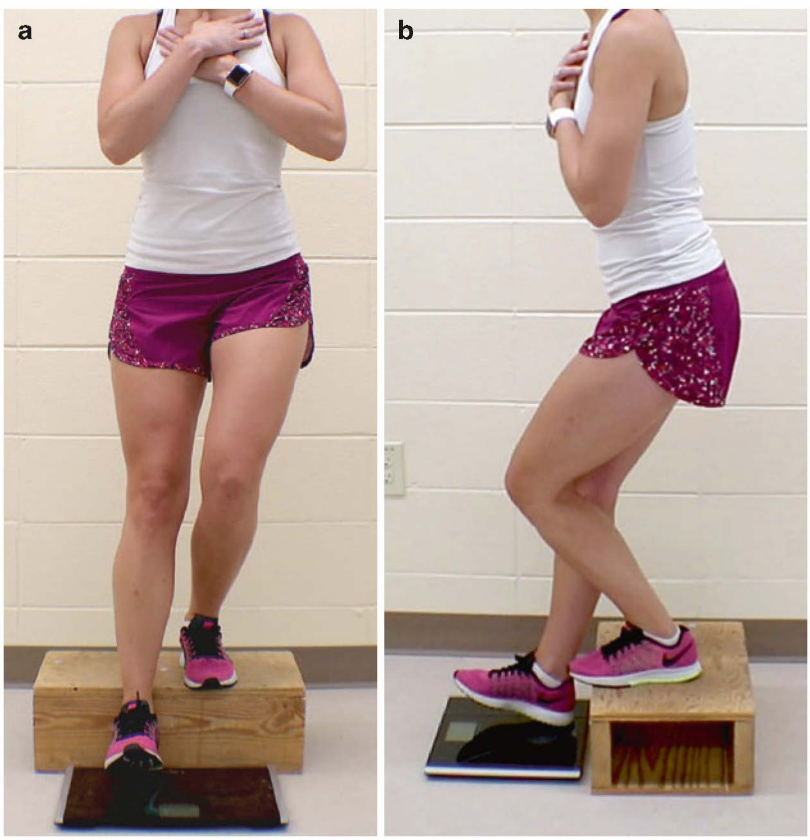

Fig. 13.5 Performance of the timed single-leg step-down test viewed **(a)** from the front and **(b)** from the side. Note that the patient touches the heel to the ground with $\leq$10% of their body weight, returns to the starting position, and performs as many repetitions as possible in 60 s

is recorded. A step down is not counted if the heel does not touch the scale; the subject places >10% body weight on the scale or does not fully bring the foot up parallel with the step. These studies highlight the potential of adding a timed single-leg step-down test to both return-to-play and pre-participation test battery for athletes. While informative, much work still remains to determine the full clinical utility and limitations of this dynamic assessment.

13.7 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 [8, 68].

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 clinically 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 [56].

As outlined in the beginning of Sect. 13.4.2, 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 [35]. This orientation can impart an excessive knee valgus moment, which is a common factor leading to ACL injury in the female athlete [11].

The incorrect performance on the single-leg step-down test is shown in Video 13.2. The hip internally rotates and adducts as the subject squats driving the knee into valgus and tibia externally rotates and foot pronates.

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. 13.6, the athlete is instructed to obtain the plank position, and a stick is placed posterior from the head to the heels. In the example shown in Fig. 13.6, 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 short period of time as shown in the bottom photograph. Correlation of the plank test, 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 13.7 provides a summary of information gained during this screening test.

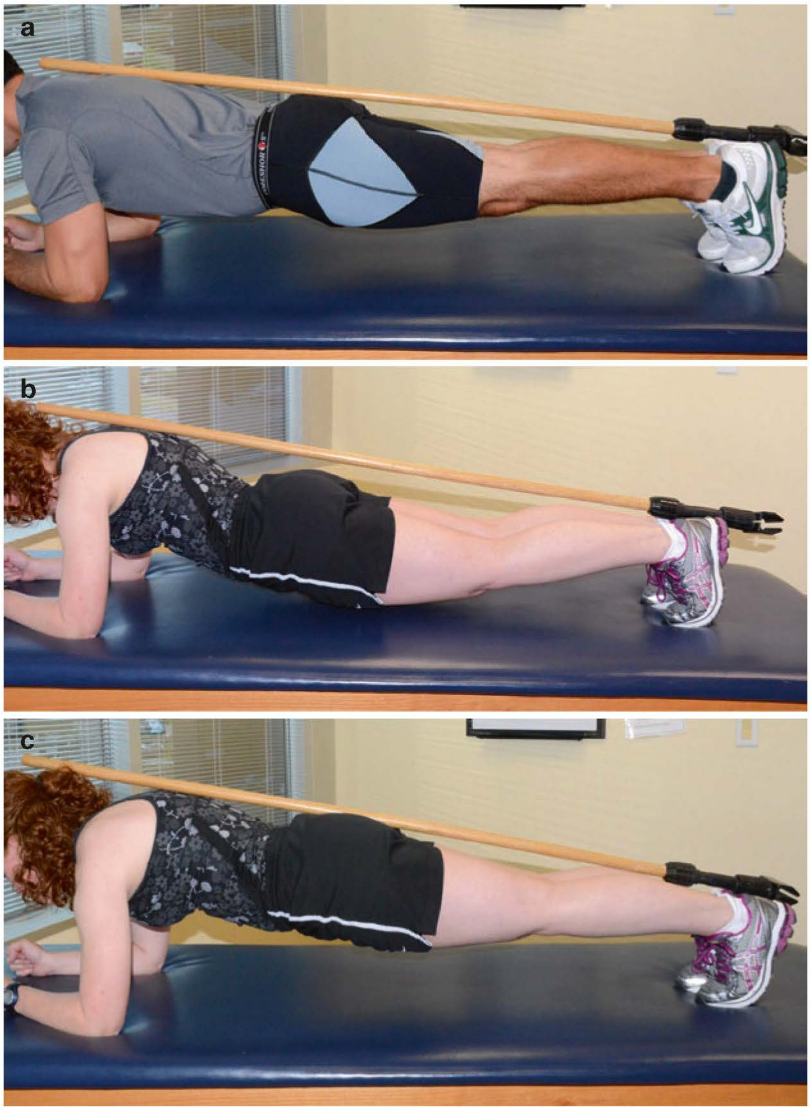

Fig. 13.6 Normal subjects performing the plank test. This test is measured by using a straight stick from the base of the skull to the feet. **(a)** The male has very little lumbar lordosis and an excellent plank position, with a posteriorly rotated pelvis and significantly greater contact with the stick than the female. **(b)** 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

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.

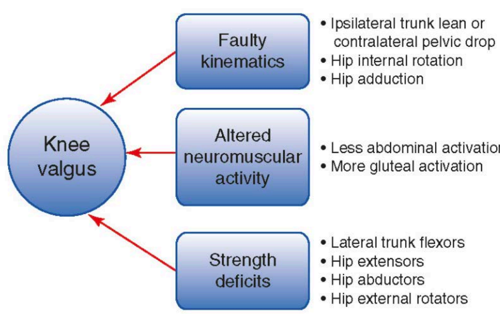

Fig. 13.7 Diagrammatic summary of factors contributing to knee valgus position. The three categories are kinematics, neuromuscular activity, and strength

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 2.44 times more likely than males to incur injury in this manner [69]. Most data have shown that females perfo1m 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 importantly, 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 impo1lantly, 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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