7 Neuromuscular Differences Between Men and Women

Timothy C. Sell and Scott M. Lephart

Abstract

Anterior cruciate ligament (ACL) injury prevention strategies have not always been successful. The identification of modifiable risk factors for injury is an important step in the injury prevention process. The gender differences observed in ACL injury rates pose an additional layer of complexity within this process; specifically, what are the sex-specific, modifiable risk factors for noncontact ACL injury? The identification of sex-specific risk factors for noncontact ACL injury facilitates the development of precise interventions. The purpose of this chapter is to outline the dynamic joint stability paradigm and provide an overview of the neuromuscular differences between men and women. The authors' studies have demonstrated that female athletes have decreased proprioception, compensatory neuromuscular control patterns, enhanced static balance, and decreased lower extremity strength compared with male athletes. These differences have resulted in altered neuromuscular control as observed in the kinematic and kinetic characteristics of the knee during dynamic tasks. Injury prevention and performance optimization must account for these differences, with specificity of training included to reduce the incidence of these debilitating ACL injuries.

7.1 Introduction

Athletes participating in a wide variety of sports are at risk of suffering significant joint injuries such as anterior cruciate ligament (ACL) rupture [1, 2]. ACL injury results in short- and long-term disabilities and includes the development of osteoarthritis that limits individuals from leading a healthy, active lifestyle [3–5]. Injury prevention strategies have not always been successful (at least in student-athlete populations), because the ACL injury rate has remained consistent for over 20 years [6–8]. This includes gender differences in ACL injury rates, a focus of this book [6–8]. Fittingly, a substantial research effort has been concentrated on the most effective injury prevention techniques, surgical protocols, and rehabilitation programs following ACL rupture [9–12].

The identification of modifiable risk factors for injury is the most important step in the injury prevention process (see Fig. 7.1) [13]. We have used this process effectively in a large military population to significantly reduce injuries [14].

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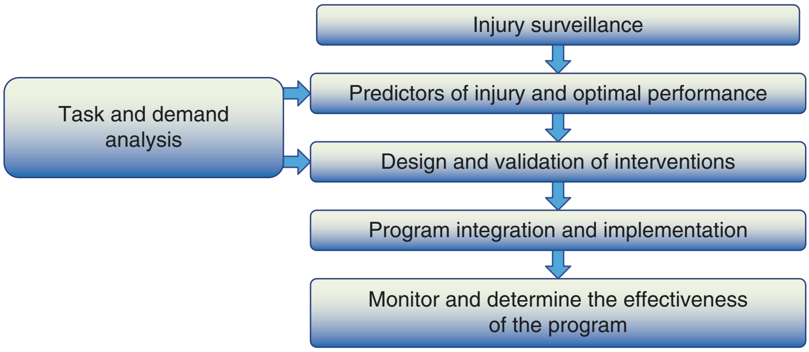

Fig. 7.1 Injury control process (From Sell TC, Abt JP, Crawford K, Lovalekar M, Nagai T, Deluzio JB et al. Warrior Model for Human Performance and Injury Prevention: Eagle Tactical Athlete Program (ETAP) - Part I. Journal of Special Operations Medicine. 2010;10(4):2–21)

The gender differences observed in ACL injury rates pose an additional layer of complexity within this process; specifically, what are the sex-specific, modifiable risk factors for noncontact ACL injury? The identification of sex-specific risk factors for noncontact ACL injury facilitates the development of precise interventions. Intervention strategies must be precise, that is, focus only on the characteristics and requirements necessary to reduce injury. Targeted and precise injury prevention is economical and efficient. It allows individuals to spend time and money on the wide range of needs necessary for care and training, which are particularly true in both student-athlete and military populations. The purpose of this chapter is to outline the dynamic joint stability paradigm and provide an overview of the neuromuscular differences between men and women. This overview will include an examination of gender differences in postural stability, muscle activation, strength, biomechanics, and the effects of fatigue on these same characteristics. The chapter will finish with a description of emerging research initiatives examining gender differences and point toward future research.

7.2 Dynamic Joint Stability and the Functional Joint Stability Paradigm

Dynamic joint stability is essential to safe and injury-free participation in sports, recreational activities, and exercise. This is particularly true at the knee because many activities place significant biomechanical demands on the lower extremity. Common athletic tasks such as stop-jump maneuvers require individuals to perform under joint loading forces that approach four times the athlete's body weight. Efficient and adequate dynamic knee stability is necessary to endure these high joint loading forces that can cause ligamentous injury [15–17]. Defined globally, stability is a state of remaining unchanged in the presence of forces that would normally change the state or condition [18]. From a physics perspective, stability can be compared to static equilibrium such that objects that remain in static equilibrium have met conditions where the sum of the forces and the sum of the moments are equal to zero (both external and internal) [19]. Joint stability can be defined as the state of a joint remaining or promptly returning to proper alignment through an equalization of forces [20]. It is a complex process that requires synergy between bones, joint capsules, ligaments, muscles, tendons, and sensory receptors [21].

The components of joint stability can be classified as either static or dynamic. The static components include the ligaments, joint capsule, cartilage, friction, and the joint bony geometry [22, 23]. The static components are typically assessed through joint stress testing and have commonly defined clinical joint stability [20]. The components provide the foundation for joint stability during functional activities by guiding joint arthrokinematics. However, the static components alone are not fully capable of providing the entire restraint necessary to prevent injury, especially during demanding tasks such as running, jumping, and cutting. The static components of joint stability work synergistically with the dynamic components of joint stability.

The dynamic components of joints stability include neuromuscular control of the skeletal muscles crossing the joint [20]. Dynamic joint stability is influenced by the neuromuscular control of the muscles crossing the joint. Neuromuscular control is the unconscious activation of the dynamic restraints occurring in preparation for and in response to joint motion and loading for the purpose of maintaining and restoring functional joint stability [20]. Neuromuscular control of joint stability involves a complex interaction between components of the nervous system and the musculoskeletal system and typically is accomplished through two different control systems: feedback and feed-forward control [24]. In a system that uses feedback control, sensors are continually measuring the parameter of interest based on an optimal value. A deviation from this optimal value will initiate an error signal. In response to this error signal, the system will trigger a compensatory response. Feed-forward systems also require measurement of a parameter, but measurement occurs only intermittently. The sensory components of this system are designed to measure a potential disturbance or change in the parameter of interest. Once a potential disturbance has been detected, the system initiates an error signal. In response to this error signal, the system institutes commands to counteract the anticipated effects of the disturbance. The commands instituted by this system are largely shaped by previous experience with similar disturbances. Feed-forward control systems are considered to be anticipatory compared to feedback control systems, which are characterized by responses only to current stimulus. Both are essential for optimal maintenance of dynamic knee stability.

The majority of research on ACL injuries and joint stability has focused on the ACL's primary role of restraining anterior translation of the tibia with respect to the femur [25]. The ACL also plays an important role in maintaining rotational stability (internal rotation [IR] and external rotation [ER] of the tibia on the femur) [26–28]. While the ACL acts as a primary restraint to anterior tibial translation, it also has a role in restraint to both valgus-varus and IR-ER rotation loading [29, 30]. Data that demonstrates the importance of the ACL in rotational stability includes the effect of injury on in vivo knee kinematics [31–33]. Using a dynamic stereo X-ray system, Tashman and colleagues demonstrated that there is approximately 10° of knee IR-ER during running [32]. After ACL injury, knee IR-ER range of motion and kinematics are altered [31, 33]. These altered kinematics may be associated with changes in the mechanical restraint that were previously provided by the ACL.

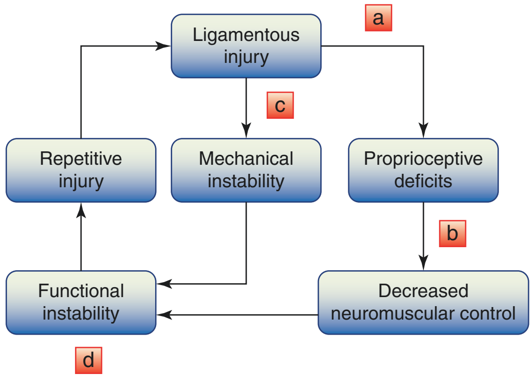

Fig. 7.2 Functional joint stability paradigm (From Lephart SM, Warner JP, Borsa PA, Fu FH. Proprioception of the shoulder joint in healthy, unstable, and surgically repaired shoulders. Journal of Shoulder and Elbow Surgery. 1994;3(6):371–80; and Lephart SM, Fu FH. Proprioception and neuromuscular control in joint stability. [Champaign, IL]: Human Kinetics; 2000)

The functional joint stability paradigm (see Fig. 7.2) was developed to demonstrate and provide a framework to examine the effects of injury, surgery, rehabilitation, and injury prevention on joint stability [34, 35]. It can also provide a framework to examine the effects of fatigue, pain, and neurocognitive changes observed following concussion. As originally described, the precipitating event (catalyst) is a ligamentous injury. This injury has a significant effect on the sensorimotor system, disruption of afferent information that previously arose from mechanoreceptors responsible for proprioceptive information (Fig. 7.2a). These proprioceptive deficits can lead to decreased neuromuscular control (Fig. 7.2b), which can be observed in altered activation (magnitude) and activation patterns (timing and coordination) of those muscles that provide the dynamic restraint (dynamic components of joint stability) for the joint. The combined effect of proprioceptive deficits and decreased neuromuscular control with a disruption (Fig. 7.2c) of a static component of joint stability (mechanical instability) leads to functional instability (Fig. 7.2d). While there are instances when an individual can maintain functional joint stability after ligamentous injury, the majority of individuals will demonstrate episodes of giving way and altered joint kinematics and kinetics. Often, individuals suffer repetitive or additional injury to other joint structures including other static components and dynamic components of joint stability.

ACL injury is an ideal model to demonstrate how the functional joint stability paradigm can be used for research, rehabilitation, and injury prevention. The primary role of the ACL is to restrain anterior translation of the tibia with respect to the femur [25]. This ligament also has important role in rotational stability (both IR-ER and valgus-varus) [28, 30, 36]. Injury to the ACL leads to both mechanical instability as measured by a knee arthrometer (examining movement of the tibia relative to the femur [37]) and proprioception [38, 39]. The subsequent effects of these proprioceptive deficits include altered neuromuscular control that, combined with mechanical instability, leads to functional instability [40–42]. There are instances when individuals can function safely and effectively without reestablishing (surgical repair of the ACL) the mechanical stability of the joint, but these instances are rare [43]. The goals of ACL reconstruction are to reestablish mechanical stability as well as restore proprioception (Fig. 7.2a, c) [44]. Rehabilitation focuses on reestablishing or improving proprioception in an attempt to improve neuromuscular control and improve functional joint stability [34, 45, 46]. Injury prevention strategies focus on maximizing proprioception, increasing strength, improving neuromuscular control, improving joint kinematics during demanding tasks to reduce joint loading, and developing movement strategies to dissipate and decrease landing forces (Fig. 7.2a, b, d) [47–54].

7.3 Proprioception

We define proprioception as the afferent information arising from the internal peripheral areas of the body that contribute to postural control, joint stability, and conscious sensations. These include the conscious submodalities of proprioception: joint position sense, active and passive kinesthesia, the sense of heaviness or resistance, and appreciation of movement velocity [55, 56]. As a component of the sensorimotor system (afferent sensory information, central processing and integration, and neuromuscular control), proprioception is essential in the maintenance of knee stability [57]. The role of the ACL is to resist anterior translation, valgus-varus, and IR-ER of the tibia on the femur [26–28]. Components of ACL (mechanoreceptors) provide afferent information essential to joint stability in addition to the mechanical stability that the ligament affords. Histological examination of the ACL has demonstrated the presence of several different mechanoreceptors including Ruffini endings, Pacinian corpuscles, Golgi-like receptors, and free nerve endings [58, 59]. Afferent information from these mechanoreceptors is integrated into the sensorimotor system and, when intact and functioning efficiently, contributes to safe and effective neuromuscular control of the lower extremity. However, any alterations in the acquisition, processing, and integration of proprioceptive information can impact functional joint stability and may result in injury.

Deficits in knee joint proprioception in female athletes may contribute to the increased rate of ACL injury because these deficits inhibit recruitment of the dynamic stabilizers that prevent anterior tibial translation. We previously examined the proprioceptive characteristics of male and female collegiate-level athletes [60]. Knee joint proprioception was measured by assessing threshold to detect passive motion (TTDPM) with a custom-built testing device that was capable of rotating the knee joint at 0.5°/s. The most important result of this study was that females demonstrated diminished proprioception when the knee was rotated from 15° of knee flexion toward full extension. We hypothesized that the decreased ability to detect motion toward a dangerous position [61–63] of full extension could interfere with the preactivation of protective muscle forces such as the hamstrings.

Given the rotation stability requirement at the knee, we designed a comprehensive study to examine the reliability, precision, and gender differences for TTDPM for IR-ER of the knee [64]. The dynamometer of a Biodex System 3 Multi-Joint Testing and Rehabilitation System (Biodex Medical Inc. Shirley, NY) was adapted and modified in order to incorporate the appropriate controls to eliminate visual, auditory, and tactile sensations that can confound results (Fig. 7.3). An air pneumatic boot (FP walker boots, Aircast, Summit, NJ) was modified so that it could be attached to the dynamometer. Each subject underwent four tests of TTDPM, two with the knee in a position of IR and two with the knee in a position of ER (Fig. 7.4). For each position, the knee was rotated toward IR and ER. Subjects were asked to notify the examiner via a switch when motion occurred and in what direction it occurred. Repeated measures demonstrated that each TTDPM test had good reliability and precision. Gender comparisons revealed that female athletes had diminished proprioception when the knee was rotated internally from both starting positions of IR and ER. Similar to movement toward full extension as observed previously, movement toward full IR loaded the ACL [28].

It may be theorized that diminished proprioception negatively affects neuromuscular control and potentially put females at greater risk for noncontact ACL injury. Unfortunately, little evidence exists that demonstrates a relationship between proprioception and neuromuscular control. We have examined these relationships and recently demonstrated a significant relationship between TTDPM and joint kinematics during an athletic task [65]. The relationship between knee flexion angle at landing, knee flexion/extension TTDPM, and strength was examined in a population of 50 physically active male adults (mean age, 26.4 ± 5.8 years). The subjects underwent TTDPM testing (knee flexion/extension), knee flexion/extension strength testing with an isokinetic dynamometer (Biodex Medical Inc., Shirley, NY), and a kinematic analysis during a single-leg stop task. Pair-wise correlation coefficients demonstrated that individuals who had better TTDPM in the direction of knee flexion and knee extension landed with greater knee flexion at initial contact with the ground.

We have continued to examine the role of proprioception in functional joint stability, especially

Fig. 7.3 Knee internal/external TTDPM setup (From Nagai T, Sell TC, Abt JP, Lephart SM. Reliability, precision, and gender differences in knee internal/external rotation proprioception measurements. Phys Ther Sport. 2012;13(4):233–7)

as it relates to gender and noncontact ACL injury [66, 67]. In the first of these studies, Clark et al. examined predictors of knee joint stability in uninjured physically active adults [66]. As part of this study, a new measure of active joint position sense (AJPS) was developed to provide greater clinical insight [68]. Reliability and precision were excellent for this measure that included eccentric-to-isometric hamstring-biased AJPS measured in a prone position. No differences in AJPS were observed between genders (see Fig. 7.5). In the second study, Keenan et al. measured trunk proprioception AJPS during a stop-jump maneuver [67]. The regression analysis revealed that trunk proprioception was not a significant predictor of knee kinematics.

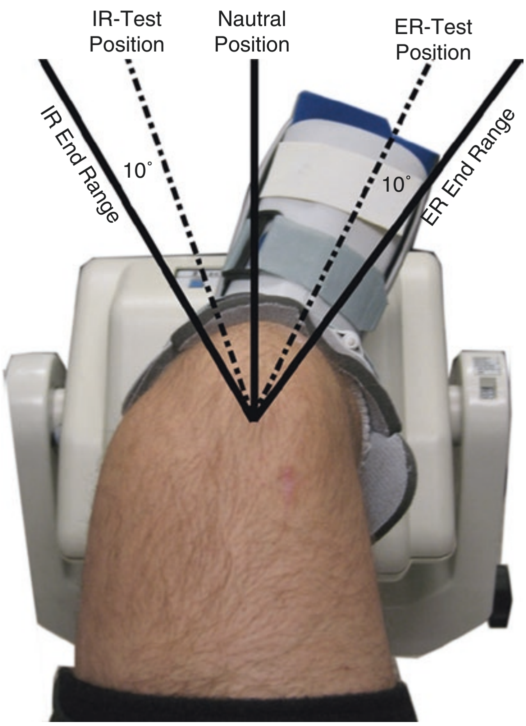

Fig. 7.4 Knee internal/external TTDPM positions (From Nagai T, Sell TC, Abt JP, Lephart SM. Reliability, precision, and gender differences in knee internal/external rotation proprioception measurements. Phys Ther Sport. 2012;13(4):233–7)

7.4 Postural Stability

Maintenance of postural stability is essential for activities of daily living, work, and athletic activities. Postural stability is frequently measured in athletic populations and in sports medicine research. It has been demonstrated to be a predictor of performance [69], is compromised after lower extremity musculoskeletal injuries [70, 71], is used in injury prevention training programs [72–75], and has been analyzed to determine risk factors for lower extremity injury [60, 76–82]. Postural stability has been defined as the ability to keep the body in equilibrium by maintaining the projected center of mass within the limits of the base of support [83]. Postural stability is often measured in research related to knee injuries since many of the same components

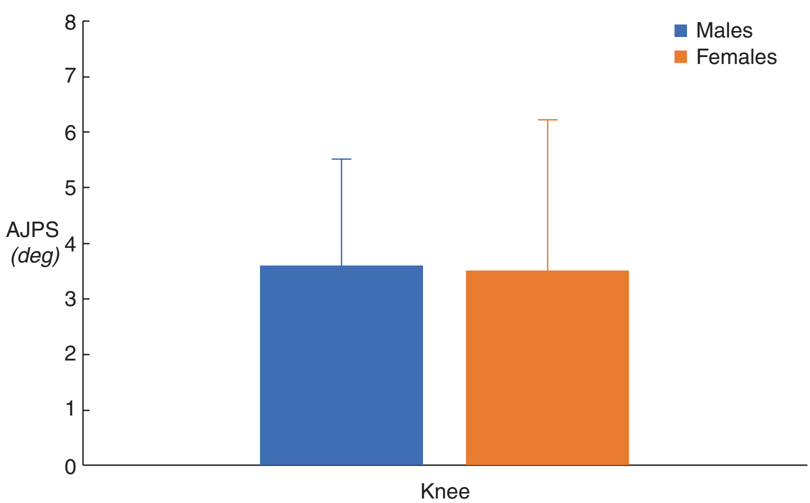

Fig. 7.5 Active joint position sense (From Clark NC, Lephart SM, Abt JP, Lovalekar M, Stone DA, Sell TC. Predictors of Knee Functional Joint Stability in Uninjured Physically Active Adults [Dissertation]. University of Pittsburgh: University of Pittsburgh; 2014

necessary for maintenance of postural stability are also necessary for dynamic joint stability. Both require establishing an equilibrium between destabilizing and stabilizing forces [84] and require sensory information from vision, the vestibular system, and somatosensory feedback [20, 85]. Postural stability is sometimes measured in studies designed to examine proprioception, but postural stability is not a measure of proprioception.

Postural stability is typically measured under two wide-ranging testing modes, static and dynamic. We define static postural stability as maintaining steadiness on a fixed, firm, unmoving base of support [86]. Typically, this is measured while an individual attempts to maintain a steady state (remaining as motionless as possible) while standing on one or two legs [87]. Dynamic postural stability has been defined as the ability to transfer the vertical projection of the center of gravity around the supporting base [87]. Another definition is the ability to maintain postural stability under changing conditions such as change in the support surface [88], following a perturbation of the individual [89, 90], or after a change in position or location such as during a single-leg jump or landing [86, 91, 92]. Dynamic postural stability has been measured with a multiple single-leg hop-stabilization test [86], a time to stabilization test [91], the star-excursion test [93], and the dynamic postural stability index (DPSI) [92]. We have examined the correlation between static and dynamic measures of postural stability [94]. The goal was to determine what measure of postural stability has the best discriminatory capability in order to predict risk of injury, especially in athletic populations. The results of this study demonstrated that static measures of postural stability as measured with single-leg static balance measures (eyes open and eyes closed) do not correlate with two dynamic measures of postural stability: anterior-posterior jump and medial-lateral jump (measured with the DPSI).

Gender comparisons in static postural stability measures provide additional evidence supporting the need to examine dynamic postural stability measures. We have examined differences in static postural stability between genders in high school athletes, college athletes, and military personnel [13, 60, 95–97]. Females demonstrated better static postural stability than males across all of these populations. We examined single-leg balance (eyes open and eyes closed) in male and female basketball players using a protocol based on Goldie et al. [87, 98]. Females demonstrated significantly better single-leg balance scores for both conditions [97]. Our research in collegiate athletes (National Collegiate Athletic Association [NCAA] Division I) using the Biodex Stability System (Biodex, Inc., Shirley, New York) [60] demonstrated that female athletes had a significantly better stability index then their male counterparts. We have completed a series of studies examining injury prevention and performance optimization with the US Army's 101st Airborne Division (Air Assault) in Ft. Campbell, KY [13]. Tactical athletes such as these soldiers suffer similar unintentional musculoskeletal injuries as civilian athletes. Static postural stability was assessed using a protocol similar to our study with high school basketball players [13, 95, 96]. Female soldiers demonstrated better static postural stability than male soldiers (lower values represent better postural stability; Fig. 7.6). The results of these three studies appear to contradict the fact that females suffer ACL injuries at a higher rate than their male counterparts in similar sports and also demonstrate diminished proprioception. Additionally, single-leg balance deficits have not been identified as a risk factor for primary ACL injury, which indicates the need for postural stability testing that presents a greater challenge to the sensorimotor system.

The DPSI has become a common measure to examine postural stability in athletic populations. Typically, the DPSI is measured during a landing task after jumping over an obstacle or after jumping a measured height [92, 94] and requires the individual to stabilize as quickly as possible after the landing. It may be a more appropriate challenge for healthy, athletic populations [94]. Previous studies have used the DPSI to examine differences between genders with mixed results [99, 100]. Both Wikstrom

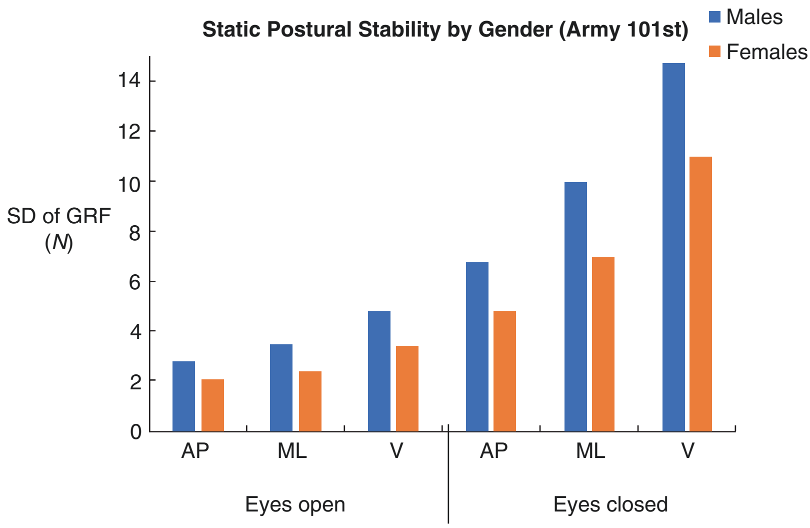

Fig. 7.6 Static postural stability in military personnel. Lower values represent better postural stability. *AP* anterior-posterior, *ML* medial-lateral, *V* vertical, *SD of GRF* standard deviation of ground reaction forces (From Sell TC, Abt JP, Crawford K, Lovalekar M, Nagai T, Deluzio JB et al. Warrior Model for Human Performance and Injury Prevention: Eagle Tactical Athlete Program (ETAP) - Part I. Journal of Special Operations Medicine. 2010;10(4):2–21)

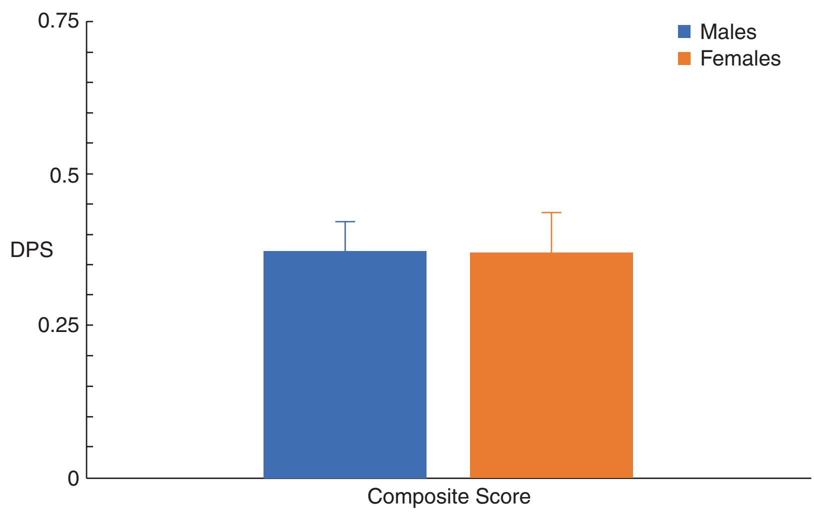

Fig. 7.7 Dynamic postural stability in military personnel (From Sell TC, Lovalekar MT, Nagai T, Wirt MD, Abt JP, Lephart SM. Gender Differences in Static and Dynamic Postural Stability of Soldiers of the Army's 101st Airborne Division (Air Assault). J Sport Rehabil. 2017:1–20)

et al. and Dallinga et al. examined gender differences during a landing task while calculating the DPSI [99, 100]. Wikstrom et al. examined an anterior-posterior jump and revealed that females had worse scores than males [100]. In contrast, Dallinga et al. demonstrated that males had inferior scores than females during similar dynamic postural stability testing [99]. Our own research in a military population (Fig. 7.7) demonstrated no differences between genders for dynamic postural stability during an anterior-posterior jump [96].

We recently completed a study designed to challenge rotational stability of the knee (transverse plane) during a landing task [101]. The task was identical to a traditional DPSI assessment except individuals were required to rotate 90° in the air prior to landing. Between-day reliability

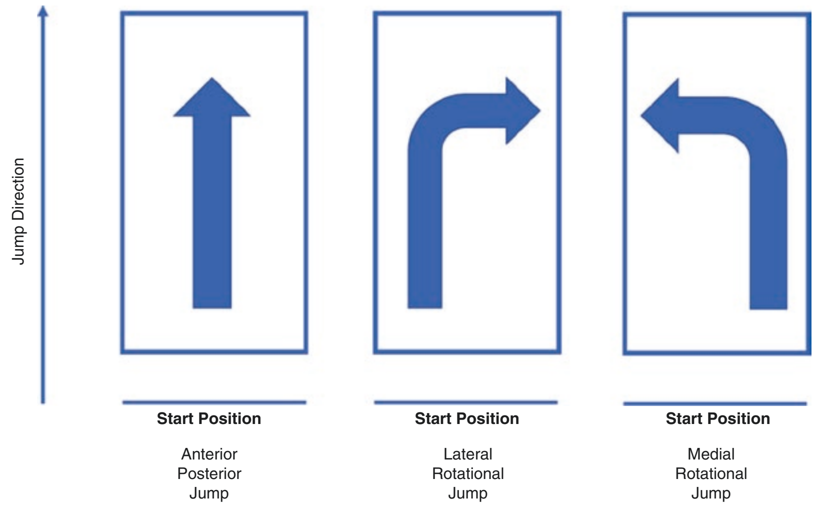

Fig. 7.8 Different jump directions for the dynamic postural stability index (From Sell TC, Heebner NR, Pletcher ER, Lephart SM. Reliability and Hamstring Activation during Rotational Dynamic Postural Stability in Healthy Recreational Athletes. The 2015 American Physical Therapy Association's Combined Sections Meeting; February 4–7, 2015; Indianapolis, IN 2015)

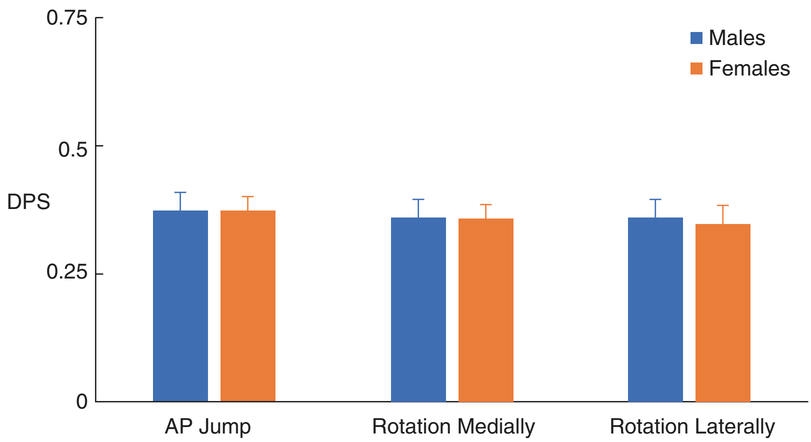

Fig. 7.9 Dynamic postural stability index across different jump directions (From Sell TC, Heebner NR, Pletcher ER, Lephart SM. Reliability and Hamstring Activation during Rotational Dynamic Postural Stability in Healthy Recreational Athletes. The 2015 American Physical Therapy Association's Combined Sections Meeting; February 4–7, 2015; Indianapolis, IN 2015)

of the rotational jump was high. There were differences between the rotational jump and the traditional anterior-posterior jump in joint biomechanics, potentially indicating a greater challenge to rotational joint stability. Gender comparisons were made across multiple jumps, including an anterior-posterior jump and the two rotational jumps (Fig. 7.8). Subjects were healthy, recreationally active, college students. No significant differences were observed for any of the jump directions for dynamic postural stability (Fig. 7.9).

7.5 Electromyographic Activity

The electromyogram (EMG) represents the electrical manifestation of the contracting muscle [102] as it transmits from the neuromuscular junction along the muscle fiber [103]. Measurement of EMG activity provides information regarding the amount of electrical activity in the contracting muscle, which in turn provides insight into the magnitude of tension developed [104]. Relative to the functional joint stability paradigm (Fig. 7.2), EMG can describe neuromuscular control as well as the attempt to maintain functional joint stability (or inability to maintain functional joint stability). Unfortunately, many variables can influence this signal which creates difficulty in interpreting these data. A direct comparison between activation levels and force production is generally not recommended. However, muscle activation patterns, amplitude, and quantity provide important insight into the neuromuscular control of joint stability.

Dynamic knee stability is dependent on the neuromuscular control over the musculature of the knee in order to reduce strain in the ACL. In order for this control to be effective, the central nervous system (CNS) must be able to anticipate destabilizing forces and act appropriately [105]. Benvenuti et al. examined EMG activity of upper arm musculature during reaction-time arm movements. These investigators demonstrated that, when destabilizing forces were anticipated, the CNS was capable of adjusting muscle activation patterns to oppose these forces. These findings support the belief that anticipatory postural adjustments are planned in detail [106]. Studies have conducted gender comparisons of EMG activity of the knee musculature during athletic tasks to quantify the role of the knee extensors and flexors in dynamic knee stability [107–109].

We have previously examined EMG activity of knee in order to determine differences between genders in dynamic stabilization strategies [60], to examine the demands of different athletic tasks [110], to determine differences between planned and reactive tasks [110], and to determine predictors of proximal anterior tibia shear force [111]. Rozzi and colleagues demonstrated that female collegiate-level soccer players activated the lateral hamstrings differently than male players during a drop-landing task. Females had a greater peak amplitude and integrated EMG (IEMG) for lateral hamstrings in response to the landing. We concluded that this finding represented an attempt by female athletes to prevent anterior tibial translation that occurs during this task. Similar observations were made in male and female high school basketball players while they performed planned and reactive stop-jump tasks [110]. Reactive tasks were included to better simulate actual athletic conditions when athletes have to react quickly to other competitors. Female high school basketball players demonstrated greater IEMG activity of the semitendinosus and a higher co-contraction value during the 150 ms prior to the initial landing compared with male players for planned and reactive tasks. These gender differences observed in semitendinosus activity during stop-jump tasks are consistent with a previous study [60] and reinforce the concept that females use compensatory strategies to counter decreased knee joint proprioception in order to achieve functional joint stabilization.

We continue to analyze EMG relative to female athletes and knee injuries. EMG activation patterns, timing, amplitude, and quantity provide insight into the attempt to achieve function joint stability in the presence of destabilizing forces and moments. In our most recent study, we determined if EMG of the medial hamstrings muscle group predicted performance during a single-leg stop-jump task [66]. We examined preactivity and reactivity (relative to initial contact) and examined its relationship to valgus-varus displacement. Preactivity explained a small, but significant, percentage of the variance in valgus-varus displacement during the single-leg stop-jump task. No gender differences in muscle activity were observed.

7.6 Strength

The dynamic components of joint stability are dependent on the characteristics and capabilities of the muscles crossing the joint [20]. One of the more important capabilities is muscular strength (force production). Muscular strength represents the ability of an individual to produce the internal muscles to counteract the destabilizing forces that occur during dynamic activities. The primary dynamic stabilizers of the knee joint are the knee flexors (hamstrings) and the knee extensors (quadriceps). Both of these muscle groups influence strain on the ACL such that an increase in hamstrings activity can reduce the amount of strain, whereas an increase in quadriceps activity can increase the amount of strain [112, 113].

Individuals with insufficient muscle strength, muscular imbalance, or inadequate activation levels and timing may not have the capability to counteract the destabilizing forces during dynamic tasks.

Our research has consistently demonstrated that males have significantly greater strength than females. Male Division I NCAA volleyball, basketball, and soccer athletes have significantly stronger knee extension and flexion strength compared with females of similar age and activity level [114]. Similar differences between genders in isokinetic knee strength have also been observed between male and female high school basketball players [97]. Strength comparisons between male and female soldiers of the 101st Airborne (Air Assault) Division have also been performed [13]. Similar to civilian athletes, male soldiers demonstrate significantly greater isokinetic knee extensor and flexor strength than female soldiers (Fig. 7.10) [95]. In addition to tradition strength measures, we have also examined time-to-peak torque [66] which represents the amount of time between the initiation of a test and maximum (or peak) torque production. Females take longer to develop peak torque production then their male counterparts (Fig. 7.11).

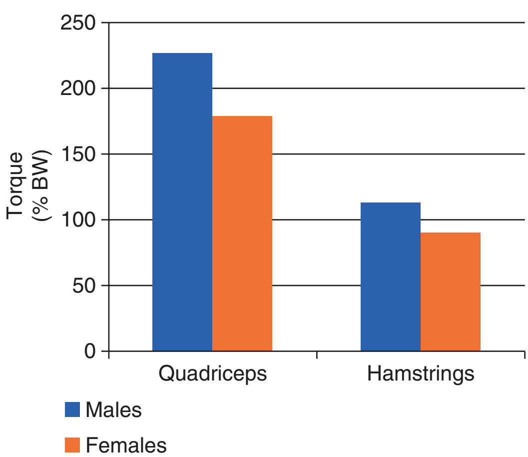

Fig. 7.10 Hamstrings and quadriceps strength in military personnel (From Allison KF, Keenan KA, Sell TC, Abt JP, Nagai T, Deluzio J et al. Musculoskeletal, biomechanical, and physiological sex difference in the US military. Army Medical Department Journal. 2015;April–June:22–32)

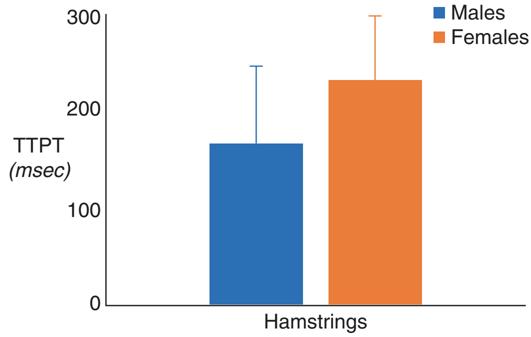

Fig. 7.11 Hamstrings time-to-peak torque (From Clark NC, Lephart SM, Abt JP, Lovalekar M, Stone DA, Sell TC. Predictors of Knee Functional Joint Stability in Uninjured Physically Active Adults [Dissertation]. University of Pittsburgh: University of Pittsburgh; 2014)

While strength testing as measured by force output is an important characteristic of the dynamic stabilizers of the knee joint, a more relevant measure for injury risk may be the hamstrings-to-quadriceps (H-Q) strength ratio. Myer and colleagues prospectively demonstrated that females who suffered ACL injury had a lower H-Q strength ratio compared with female controls and male controls who did not suffer ACL injury [115]. These investigators also demonstrated that females who subsequently suffered an ACL injury had lower hamstring strength, but not lower quadriceps strength, compared with males who did not suffer an ACL injury. Our studies have consistently demonstrated that females and males have similar H:Q strength ratios when using similar isokinetic speeds (Fig. 7.12). It is important to note that our studies represent comparisons between uninjured male and female groups.

We have examined isometric IR-ER strength in male and female athletes, as well as the relationship between knee flexion/extension strength and landing kinematics [65]. Internal and external isometric strength was measured with a similar setup as described with TTDPM testing. Female athletes demonstrated lower IR and ER strength compared with male athletes (Fig. 7.13). These results are consistent with other gender comparisons in knee strength. Nagai and colleagues also demonstrated a significant relationship between knee extension strength and knee

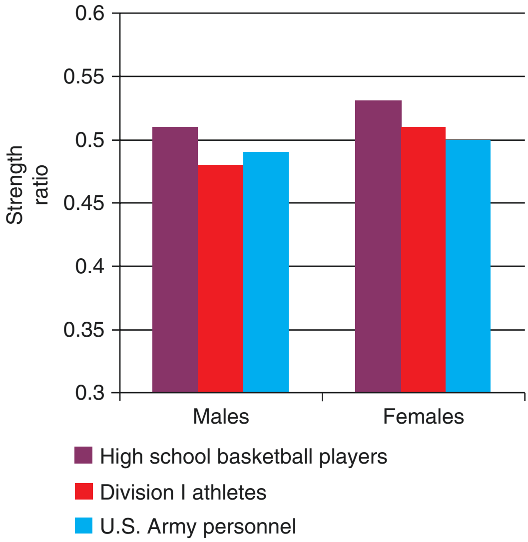

Fig. 7.12 Hamstrings-quadriceps strength ratios across athletes and military personnel

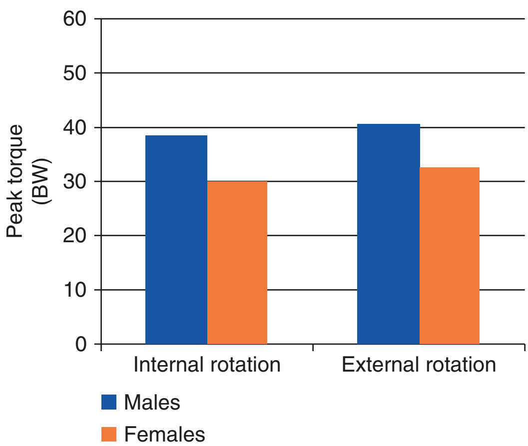

Fig. 7.13 Knee internal/external rotation strength

flexion angle on landing; as quadriceps strength increased, so did knee flexion angle at initial contact [65]. In terms of ACL injury, landing in a more flexed position is safer than landing in an extended position [28, 116, 117]. Isolated knee strength measurements only describe the force production capabilities of the movements tested. Combining knee strength testing with other measures of functional joint stability such as landing kinematics, and examining the relationship between each, gives a better picture of the interaction between the variables and provides insight into strategies of maintenance of functional joint stability.

7.7 Biomechanics

The functional joint stability paradigm (Fig. 7.2) demonstrates that deficits in proprioception, EMG activity, and strength may affect neuromuscular control and knee joint stability. Neuromuscular control and knee joint stability may be further examined through motion analysis and calculation of relevant knee biomechanical variables such as joint kinematics and joint kinetics. We have examined the biomechanics of males and females performing several different tasks in order to determine how neuromuscular control (deficits) affects landing kinematics and kinetics. These studies demonstrated that female athletes typically land with greater vertical ground reaction forces, greater peak posterior ground reaction forces, greater proximal anterior tibia shear force, increased hip internal rotation, less knee flexion, and greater knee valgus compared to their male counterparts [110, 114]. Our research with the military includes gender comparisons between male a female soldiers of the 101st Airborne (Air Assault) Division while performing a vertical drop-landing task. We analyzed the valgus-varus position of the knee at initial contact for each task. Females performed the vertical drop-landing task in greater valgus than males [95]. While males landed in a varus position, females landed relatively close to neutral valgus-varus position (Fig. 7.14).

Measurement of knee biomechanics continues to be an important aspect of assessing functional joint stability. We have begun to examine different instrumentations to measure knee biomechanics that does not depend on brick-and-mortar research laboratories. We are currently comparing three-dimensional accelerations of the tibia measured with skin-mounted accelerometer to knee joint forces measured through inverse dynamics and tibial acceleration and translation compared with dynamic stereo X-ray system. Current research has been expanded to

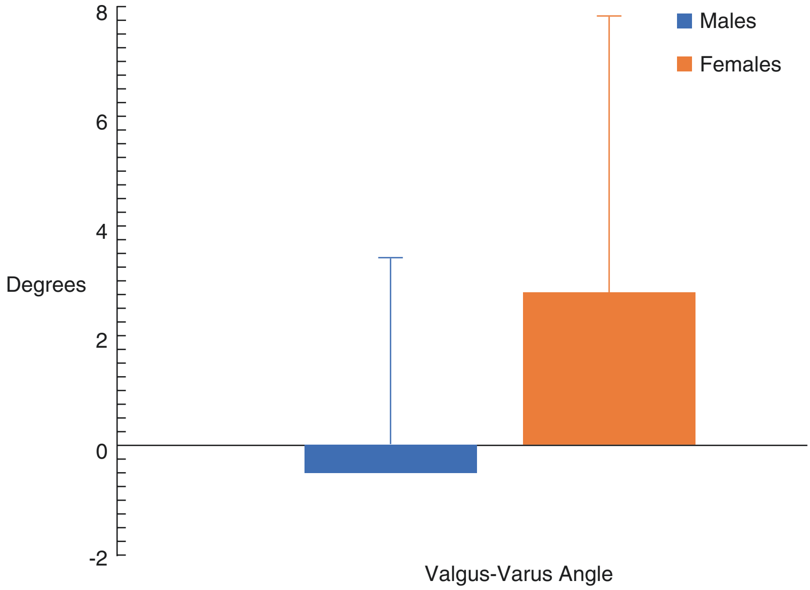

Fig. 7.14 Knee valgus-varus angle during a vertical drop landing (From Allison KF, Keenan KA, Sell TC, Abt JP, Nagai T, Deluzio J et al. Musculoskeletal, biomechanical, and physiological sex difference in the US military. Army Medical Department Journal. 2015;April–June:22–32)

incorporate emerging technology, including the use of wireless three-dimensional inertial sensors that have the potential to be used during actual competition. The ultimate goal of this research is to develop robust but portable instrumentation to collect relevant biomechanical data away from traditional laboratory environments.

7.8 Fatigue

Fatigue creates an environment in which more musculoskeletal injuries occur, whether it is within a single game/competition or within a series of closely scheduled games [118–124]. These observations include muscular injuries, joint injuries, and noncontact ACL injuries [125]. Muscular fatigue can disrupt or degrade the compensatory stabilizing mechanisms necessary to maintain joint stability in the presence of destabilizing forces and moments [80]. Although the exact mechanisms are unclear, the disruption of normal stabilizing mechanisms may decrease neuromuscular control [126, 127], increase knee joint laxity [80, 128, 129], decrease balance skill [126], and decrease proprioception [130–133]. We have conducted several studies examining the effects of fatigue on neuromuscular and biomechanical characteristics.

We have examined knee joint laxity, kinesthesia (via TTDPM), lower extremity balance, and surface EMG activity during a landing maneuver of male and female athletes before and after a peripheral muscular fatigue protocol [80]. The protocol was designed to induce fatigue of the knee flexors and extensors and was implemented using a Biodex isokinetic dynamometer. Peripheral fatigue decreased the time to detect motion, increased the contraction onset time after landing for the medial hamstrings and gastrocnemius, and increased IEMG of the vastus lateralis and vastus medialis after landing. Both males and females were affected equally. We have also demonstrated fatigue, induced by an exhaustive run [134, 135], forces adaptations in landing kinematics equally in both genders [136]. Both male and female recreational athletes demonstrated a decreased knee flexion angle at initial contact and a decreased maximum valgus angle which were theorized to be an attempt to promote knee stability. Overall, it appears that fatigue affects both genders equally and places both male and female athletes at greater risk for injury.

We have conducted several studies regarding the relationship between physiological characteristics such as anaerobic capacity, aerobic capacity, and muscular endurance to determine the effects of fatigue on neuromuscular and biomechanical risk factors for injury. During a pilot study, we induced fatigue using a maximum oxygen uptake treadmill test and a test of anaerobic power and capacity. Both protocols significantly affected postural stability during a single-leg balance task that persisted for 8 min. We recently completed a study examining the effects of fatigue (whole body exercises and multiple bouts of running) on knee proprioception measured by TTDPM [137]. Fatigue was verified through ratings of perceived exertion, heart rate, and blood lactate measures. No changes in proprioception were observed post-fatigue, but there was a significant relationship between aerobic capacity and proprioception that may indicate highly trained individuals have better proprioception.

Fueling, or feeding, is one potential intervention to prevent the onset of fatigue and its potential as a risk factor for noncontact ACL injury. We examined the effects of carbohydrate-electrolyte feedings on knee biomechanics and dynamic postural stability during intermittent high-intensity exercise to fatigue [138]. The fatigue protocol was designed to simulate a basketball game, including timing of quarters and physical activities performed. Fatigue induced changes in landing biomechanics such as knee flexion angle at initial contact during single-leg jump landings and dynamic postural stability. The feeding used in this study had little to no effect on knee biomechanics or dynamic postural stability. Nutrition and physical training and their relationship to fatigue-induced risk factors for noncontact ACL injury are an important area of research; however, few research studies have examined these interventions to date. Both nutrition and physical training strategies may be important to examine more closely in the future.

7.9 Current Research and Emerging Concepts

We continue to study gender differences between males and females in athletic and military populations, focusing on reducing the risk of injury as well as optimizing human performance. These objectives are not mutually exclusive, as improving performance and reducing injury risk can be accomplished simultaneously. This is especially true in environments where fatigue impacts injury risk. Performance optimization solely focusing on fitness (aerobic and anaerobic) can significantly impact injury risk [139]. Our research with the military, specifically examining the different injury risk profiles, task requirements, and demands of different mission types, demonstrates an increasing need for specificity of training relative to the physiological, musculoskeletal, and neuromuscular demands. We should not discount the role of the CNS in injury prevention. There is a mounting body of evidence indicating that brain injuries such as sports-related concussions increase the risk of injury [140–145]. This risk factor seems to be gender neutral. We are examining sports-related concussion as a risk factor for lower extremity injury in an attempt to develop a measurement or assessment tool to be added to medical clearance guidelines for return-to-play following concussion. This tool would screen for risk of lower extremity injury. Finally, the reinjury rate after ACL reconstruction is approaching 30% [146]. There is a critical need to develop better decision guidelines for this population and potentially explore if females require different rehabilitation strategies.

7.10 Summary

The functional joint stability paradigm provides the framework for mechanistic studies examining neuromuscular differences between men and women. The injury prevention process provides the steps to conduct high quality injury prevention research. Our studies have demonstrated that female athletes have decreased proprioception, compensatory EMG patterns, enhanced static balance, and decreased lower extremity strength compared with male athletes. Some of these same differences have also been observed in female military personnel. These differences have resulted in altered neuromuscular control as observed in the kinematic and kinetic characteristics of the knee during dynamic tasks. Injury prevention and performance optimization must account for these differences with specificity of training to reduce the incidence of debilitating ACL injuries.

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