Dynamic Balance Testing and Perturbation-based Neuromuscular Exercise Training in Healthy and ACL-injured Adolescent Females

By

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Abstract

Physically active adolescent females are at significantly greater risk for anterior cruciate ligament (ACL) injury than their male counterparts when participating in the same sports. While preventative neuromuscular (NM) exercise programs can reduce injury rates and improve function, they are not practical or safe for the ACL-injured individual. The effectiveness of a perturbation-based NM training program that is appropriate for the ACL-injured, physical active individual has been established for an adult population but has yet to be investigated in the adolescent female population. Scoring from two common clinical tools, the Star Excursion Balance Test (SEBT) and Y-Balance Test (YBT), are used to screen athletes at risk of injury, assess deficiencies after injury, and monitor progress in rehabilitation, are known to vary by age, sex and sport. Currently, there is little research examining performance and scoring on clinical dynamic balance tests in adolescent females who are healthy or ACL-injured and awaiting the standard of care, surgical reconstruction. This investigation used an evidence-based approach to investigate the utility of clinical dynamic balance testing and the effectiveness of a perturbation-based NM exercise program in healthy and ACL-injured adolescent females. Reach performance measures and injury classification of clinical dynamic balance tests should not be used interchangeably for physically active adolescent females as differences between the measured reach directions and injury classification were observed between the SEBT and YBT. Surprisingly, healthy and ACL-injured adolescent females demonstrate similar reach distances on the YBT. Although healthy adolescent females demonstrate a relationship between BMI, lower extremity strength, and the YBT, no such relationship exists for ACL-injured. Specific analysis of the YBT anterior reach direction indicates that both healthy and ACL-injured adolescent females demonstrate a variety of joint movement strategies to achieve a similar

maximal reach distance. Finally, our results suggest that perturbation-based NM training is safe, but offers limited benefit for healthy adolescent females and no preoperative benefit to ACL-injured adolescent females. These findings provide researchers and clinicians with information which could potentially advance the current standard of care used in the assessment, prevention and pre-operative management of ACL-injured adolescent females.

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List of Manuscripts for Publication

This thesis is based on the following manuscripts published, submitted or undergoing revisions for peer reviewed publication.

I. Bulow, A., Anderson, J., Leiter, J., MacDonald, P. & Peeler, J. The star excursion balance and Y-balance tests differ when assessing physically active healthy adolescent females, publication in International Journal of Sport Physical Therapy, 2019 April; 14(2); 192-203.

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III. Bulow, A., Bellemare, A., Anderson, J., Leiter, J., MacDonald, P. & Peeler, J. Lower limb kinematics of the Y-balance test anterior reach direction in adolescent females, undergone peer-review for publication, currently being edited for re-submission.

IV. Bulow, A., Anderson, J., Leiter, J., MacDonald, P. & Peeler, J. Safety and Effectiveness of a perturbation training program on dynamic balance in adolescent females, submitted to Clinical Journal of Sport Medicine.

Chapter 1 - Thesis Introduction

1. General Introduction

A rupture of the anterior cruciate ligament (ACL) is one of the most common traumatic knee injuries observed in a pediatric population[1–4]. Unlike other ligamentous injuries, the ACL cannot heal itself. This creates knee joint instability and leads to dramatic functional deficits. Adolescents with prolonged ACL deficiency are at considerable risk of injury to other structures of the knee[5–9]. They have a 4-fold increase in the occurrence of meniscal injuries[5], an 11-fold increase in chondral lesions,[5] and are highly susceptible to the early onset of the knee osteoarthritis, with more than 50% of patients developing knee osteoarthritis (OA) within 20 years of their initial injury[8,9]. To put this in perspective, a girl who tears her ACL at 12-yrs-of-age while playing recreational soccer will have a 1in 2 chance of developing significant signs of advanced joint degeneration, by the time she is 32-yrs-of-age: "*the young patient with an old knee*"[10].

In North America, more than 250,000 ACL ruptures are reported on an annual basis[11], with the frequency of ACL rupture growing the fastest in physically active adolescents between the ages of 10 and 12 years[12]. The most at-risk individuals are female adolescents, who are 2-6 times more likely to sustain an ACL rupture than their male counterparts[3,4,13]. The current standard of care for patients who have ruptured their ACL is surgical reconstruction[14,15]. However, female sex and open growth plates are patient characteristics that can influence a surgeon's decision to perform or delay surgical reconstruction[14]. Beyond this, delays associated with long surgical wait lists can sometimes mean that a significant amount of time can elapse between the time of initial ACL injury and surgical intervention (in Winnipeg the average wait time has been documented to be as long as 438 days[16]). As a result adolescents are often recommended to initially follow a conservative non-operative rehabilitation approach until surgical reconstruction is possible[15,17].

In order to minimize secondary injuries and improve patient outcomes following ACL rupture, evidence-based rehabilitation interventions need to be developed to supplement the current standard of care. Recently, research has emerged which suggests that ACL rehabilitation programs that emphasize progressive neuromuscular (NM) training prior to[18–24], and following ACL surgical reconstruction[19,25–27] significantly improve knee function in adults. Currently ACL rehabilitation protocols targeting adolescents incorporate activity modification with basic exercise prescription (i.e., range of motion and strength exercises), but do not emphasize NM exercise training. The time delay between injury and surgery is an optimal period to incorporate a supplementary NM exercise program. Additionally, injury prevention research suggests that incorporating NM exercise training during early adolescence optimizes knee function[28] and can reduce the rate of ACL ruptures in adolescents by as much as 50%[29–32]. The incorporation of NM exercise training into the current standard of care for ACL-injured adolescents may help to improve short and long term outcomes associated with ACL rupture.

The objective of NM training is to improve dynamic joint stability, generate fast and optimal muscle activation and decrease joint forces[33]. Fitzgerald et al. have established a perturbation-based NM exercise training protocol proven to be safe and effective in the ACL-injured adult population[33]. This type of training consists of exercises that require the patient to maintain balance on a support surface while a clinician administers purposeful manipulations of the support system[20]. Unfortunately, to date the safety and effectiveness of this specific perturbation-based NM exercise training has not been reported in healthy or ACL-injured adolescents.

Currently there is no "gold standard" for measuring balance, as laboratory-based and clinical methods of measuring dynamic postural stability assess different components of balance[34]. Clinicians often use dynamic balance tests as a functional screen to identify athletes at-risk of

injury, assess deficiencies following injury, and monitor rehabilitation progress[35]. Two reliable methods commonly used to clinically assess dynamic balance of the lower extremity are the Star Excursion Balance Test (SEBT)[36,37] and Y-Balance Test (YBT)[38,39]. Both tests simultaneously assess range of motion, flexibility, neuromuscular control and strength[40]. Within an healthy adult population reach distances and kinematic profiles differ between the SEBT and YBT suggesting that the values between tests should not be used interchangeably[41,42]. Also, normative dynamic balance performance scores vary depending on the age, sex or specific sport played of the population[43–49]. While there are many investigations of adults and collegiate populations the literature lacks information regarding scores from clinical dynamic balance tests for active adolescent females. As such, clinicians may be incorrectly classifying young female athletes based on interchanging indices of performance between the SEBT and YBT, or using injury risk thresholds that were established using a different population. The relationship between the two dynamic balance scores for the adolescent female population is currently not known, and is of particular interest as this demographic carries a higher risk of sustaining lower extremity injuries, specifically to the ACL.

There is currently little research which has examined SEBT scoring, YBT scoring, or perturbation-based NM exercise training protocols in adolescent females who are healthy or ACL-injured and awaiting the standard of care, surgical reconstruction[50]. This investigation will use an evidence-based approach to investigate the effectiveness of a perturbation-based NM exercise program in healthy and ACL-injured adolescent females, as well as the utility of clinical dynamic balance testing such as the SEBT and the YBT. These findings will provide researchers and clinicians valuable knowledge that will help inform them about the prevention, assessment,

and rehabilitation of injuries in adolescent females and may reduce the risk of developing the debilitating secondary injuries to the knee joint.

2. Review of Literature

2.1 Structure and Function of the Knee Joint

The knee is a modified hinge joint, which primarily allows flexion and extension motion with some secondary rotation, when in a flexed position[51]. The bony articulation of the concave distal femoral condyle on the relatively flat tibia plateau provides minimal contributions to the stability of the knee joint. Thus, ligamentous connections and surrounding musculature are heavily relied upon for stability[52]. The joint capsule and collateral ligaments provide additional support when the knee is extended, however they become increasing slack as flexion proceeds. The ACL is the primary passive restraint to anterior tibial displacement on the femur; its secondary role is to aid in resisting internal and external rotation. While the posterior cruciate ligament (PCL) functions to prevention posterior femoral displacement on the tibia, as when walking downhill[52]. The medial and lateral menisci are critical secondary stabilizers to anterior tibial translation [53,54]. Compressive (axial) loading on the tibiofemoral joint increases joint congruency and improves joint stability, even in the absence of the meniscus[55]. Interestingly, when transitioning from the non-weight bearing to weight bearing phase during the gait cycle (foot strike with the knee near full extension), axial loads and anterior tibial translation are the greatest[56]. The quadriceps and hamstring muscles groups primarily function to extend and flex the knee joint, respectively. When the knee is flexed, the secondary role of the hamstrings is to medially and laterally rotate the tibia. Additionally, the hamstrings muscles act synergistically with the ACL to prevent anterior tibial translation (agonist), while the quadriceps are an antagonist to the ACL[52,57]. Muscles of the ankle and the hip joint also play an important role in minimizing the strain on the

ACL. Similar to the quadriceps, the gastrocnemius increases strain on the ACL, while the soleus decreases strain on the ACL by generating a posterior tibial force similar to the hamstrings[58,59]. The gluteus medius, gluteus maximus and piriformis oppose knee valgus moments, and thus also have the potential to protect the ACL from injury[59].

2.2 Structure and Function of the Anterior Cruciate Ligament

The ACL is a critical structure in maintaining a functionally stable knee joint. The ACL is an intra-articular, extrasynovial ligament that is considered the primary restraint to prevent anterior tibial displacement on the femur. The secondary role of the ACL is to aid resisting internal and external rotation. The ligament courses posteriorly and laterally as it ascends from the anterior area of the tibia to the posteromedial aspect of the lateral femoral condyle[52,60]. The highly organized collagen matrix can be divided into two separate functional and anatomic bundles: the anteromedial (AM) and the posterolateral (PL) bundle. At different stages of knee flexion-extension movements, different portions of the ACL provide stabilization to the knee joint: the AM bundle is stressed the most in flexion, while the PL bundle is most taught in extension[60–62]. The major blood supply of the cruciate ligaments arises from the middle geniculate artery, with the vasculature descending obliquely over the ligament beneath the synovial membrane[63]. The distal part is provided with a small about of blood by branches of the lateral and medial inferior geniculate artery. The ligament has poor healing properties especially after mid-third interruptions, since the vessels of the synovial network from the inferior genicular arteries are insufficient for ligament vitality[63]. The ACL is innervated by the posterior articular branches of the tibial nerve. These fibers penetrate the posterior joint capsule and course through the synovial lining of the cruciate ligaments[64]. Neuronal elements include Ruffini endings, Pacinian corpuscles, Golgi tendon organs receptors and free-nerve endings[64]. The presence of neuronal

tissue accounts for 1-2.5% of the total volume of the ACL[65,66]. Although receptors have been found in the mid-section of the ligament[66], the highest concentration is at the femoral and tibial insertion points[64,65,67]. Interestingly the mid substance of the ligament is most compliant to the applications of strain, while the end points are stiffer. The higher concentration of receptors in the stiffer end sections may have a threshold to detection function. If a load reaches a high enough level to cause a strain at the ends of the ligament, a large number of receptors will be vigorously triggered to indicate the danger. During typical movements, monitoring of tissue strain will be ongoing, however overshooting will be prevented with less receptors in the pliable mid-substance[68]. Thus the ACL can provide the central nervous system (CNS) with sensory and proprioceptive information. Conversely, a disruption of the ACL would not only disrupt the mechanical strength of the knee but would also contribute to the functional instability commonly reported with ACL injuries due to a deficit in proprioceptive feedback.

2.3 Structure and Function of Knee Joint Proprioception

Historically, the ability of the various tissues to maintain mechanical and structural stability of the knee has been of utmost importance. However, it has been widely documented that passive stability, as determined by clinical laxity tests, does not equate to functional stability[61,65,67,69–75]. In addition to the passive mechanical restraints, tissue provides important proprioceptive information for a functional knee joint to ensure that the joint is stable and asymptomatic during activities of daily living and physical activity[69]. Proprioception refers to the complex interactions between the sensory and motor pathways, as part of the sensorimotor system[76,77]. Proprioception is the specialized sensation that encompasses three components; 1: static awareness of joint position; 2: awareness of joint movement and acceleration (kinesthesia); 3: closed-loop efferent activity, which starts a reflex response and regulates muscle activiation[78]. A mechanoreceptor

converts the mechanical energy from a proprioceptive stimulus into an action potential, which is transferred to the central nervous system (CNS). This information is processed via different pathways to create a neuromuscular response[65,76].

Mechanoreceptors

The presence and role of mechanoreceptors in the function of the knee joint has been extensively investigated. Five types of receptors have been located in the various passive and dynamic structures of the knee joint: Ruffini endings, Pacinian corpuscles, Golgi tendon organs (GTO), Muscle spindles, and Free nerve ending. The mechanoreceptors within the various knee joint structures have different morphology and different responses to mechanical stimulus. They monitor typical physiological movements such as pressure, bending, joint position and rate of motion, as well as potentially damaging stimuli[68]. Two theories have been proposed to describe how information from each of the specific mechanoreceptors is conveyed to the CNS: 1. the labelled line theory; and 2. The ensemble coding theory[77,79]. The labelled line theory assumes that each unique proprioceptive stimulus triggers a specific receptor, which connects a particular nerve fiber to a precise termination point in the CNS. However, this theory has been criticized based on the fact that most receptors are sensitive to different types of stimuli. The ensemble coding theory is more widely accepted. It assumes that several mechanoreceptors will respond to a given proprioceptive stimulus, or set of stimuli, and the neural population will transmit the information to the CNS. Even though each receptor has a different response, their range of sensitivity is specific, yet overlapping with other receptor types[77,80]. Thus, knee joint stability is obtained when the sensory receptors, neural projections, and connections of the bones, joint capsule, ligaments, menisci, and muscles function synergistically[68].

Both the feedback and feedforward mechanisms of control are used in the processing of somatosensory information regarding proprioception and pain. Feedback control occurs when the detection of a sensation initiates a corrective response within the system. The process often involves a delay from the time a stimulus is applied and activates a mechanoreceptor, to the initiation of a motor response. In feedforward control, previous experiences with a stimulus allow for the preprogramming of anticipatory actions to occur quickly[77,80,81].

Central Nervous System Pathways

After a proprioceptive stimulus (afferent signal) is converted into an action potential by a mechanoreceptor, the message is relayed to the CNS for processing of a motor response (efferent signal). Information from the mechanoreceptors is processed via different pathways and at different levels of the CNS. Reflexes are subconscious stimulus-responses mechanisms controlled at the spinal cord level. Subconscious and stereotypic repetition movements, such as walking or swimming, are controlled by a circuit of neurons in the lower brain stem and cerebellum. Conscious, specific and goal-directed movements occur when the neural network reaches the level of the cerebral cortex[82].

Ascending Somatosensory Tracts

In addition to the spinal reflexes, mechanoreceptors of the knee joint transmit proprioceptive and pain information to the cerebral cortex and cerebellum via three ascending tracts: 1. Dorsal column; 2.Spinocerebellar; and 3. Spinothalamic. A chain of long neurons and interneurons conduct the stimuli from the receptor to ascend the spinal cord and terminate at the somatosensory cortex or cerebellum[82].

Cerebral cortex

The relatively consistent pattern of gyri and sulci has allowed researchers to identify specific functions of the cortical areas, of which Brodmann's classification system is the most commonly utilized[82]. The primary sensory area (Brodmann's: 3, 1 ,2) is located on the post-central gyrus of the parietal lobe. This area receives the somatosensory information from the thalamus for processing the conscious perceptions of the somtatosensory information, such as proprioception and pain[82]. The primary motor area (Brodmann's: 4) is located on the pre-central gyrus of the frontal lobe. Anterior to this area is the premotor cortex (Brodmann's: 6).These areas are responsible for the planning, initiation and activation of voluntary muscle contractions. Most of neurons for the descending corticospinal tract are located here[82].

Descending Motor Tracts

As previously mentioned, the regulation of motor responses occurs at different levels. Free-nerve endings, muscle spindles and GTO's have stimulus-response mechanisms at the spinal cord to initiate reflexive muscle responses. The cerebellum coordinates the force, extent and duration of muscle contractions to ensure accuracy and precision of voluntary movements of the extremities. Motor control areas of the cerebral cortex control voluntary muscular contractions of the extremities via myelinated axons descending through the lateral corticospinal tract.

Neuromuscular Response

Dynamic neuromuscular response is the result of the detection and processing of proprioceptive information. A joint is dynamically stabilized when the appropriate muscles and sequence of activation occurs. Muscular response is determined by two factors, the site of afferent reception (mechanoreceptors in a periphery or a central site) and the location of the signal processing center (spinal cord or cerebral cortex). Muscle activity can be classified as automatic (reflexive), semiautomatic or voluntary. Automatic or reflex responses are typically gross, quick movements

that require no cortical processing or sensory feedback and are generated by a local stimulus. Semiautomatic movement which is typically rhythmic in nature, such as walking, usually requires supraspinal contributions to start and end the movement but the neural control proceeds automatically. These movements require neural networks in the spinal cord, brain stem and cerebellum. Cortical activity controls complex voluntary movements. These tasks can be learned and practiced so that the amount of conscious effort required for each step of the task can be decreased over time and as a result the task can be accomplished quicker and with less cortical involvement[83]. The appropriate or normal neuromuscular responses of the knee joint will be discuss below in reference to the responses that are observed in ACL-injured individuals.

2.4 Anterior Cruciate Ligament Injury

The majority of ACL injuries occur from non-contact torsional stress, when the knee is close to full extension during a sharp deceleration or pivoting manoeuver[84]. Although it can vary based on sex and age, rupture of the ACL often occurs at stress levels above 1725 N. Interestingly, loads on the knee joint and ligament frequently exceed this force during vigorous physical activities[60,69,74]. Increased joint stability and decreased tension of the ACL occurs with increased loads on the joint to compress the tibiofemoral geometry (weight bearing)[55,85]and simultaneous contraction of quadriceps and hamstring muscles increase joint stiffness[86–90]. In addition to its role as a passive stabilizer, the ACL provides sensory and proprioceptive information that is a key factor in the maintenance of functional knee stability[61,64–67,91–94]. As ACL injuries are one of the most common traumatic knee injuries observed, research on the mechanical and proprioceptive role of the ACL has been extensive. Although many studies have been conducted, the specific nature of the impact of an ACL injury on knee proprioception and function remain unclear.

Impact of ACL Injury on Mechanical Support

ACL-deficiency changes kinematic and tibiofemoral contact mechanics. Increased forces in the posterior-central aspect of the medial tibial plateau[95], medial femoral condyle[96] and lateral meniscus[96] have been noted. These altered loading patterns provide a biomechanical rationale for the high incidence of meniscal injuries and chondral lesions found subsequent to ACL injury[95–98]. Adolescents with prolonged instability due to ACL deficiency are at significant risk of secondary meniscal tears, chondral injuries and developing early onset knee OA[5–9]. Instrumented testing (KT-1000), clinical examinations (anterior drawer, Lachman and pivot shift tests) are techniques used to assess passive joint laxity, and MRI and arthroscopy are often used to confirm a rupture of the ACL. However, numerous studies have indicated that mechanical laxity does not relate to functional outcome scores[69,71–73,76,94,99]. An ACL-injured knee moves along a non-physiological axis which alters the normal stress and proprioception of the remaining anatomical structures[96,100,101]. The ability of the other structures, primarily the muscles, to compensate for a lack of support from the ACL will determine the functional outcome of the knee joint[102]. Individuals who are able to compensate well for the increased tibial translations are defined as copers. Typically they are able to coordinate muscle activity to dynamically stabilize the knee so that they are able to resume preinjury activities without episodes of knee giving-way, and are successful following a non-operative management regime. Non-copers do not have dynamic stability and experience episodes of giving-way with activities of daily living and sports participation[99,103].

Impact of ACL Injury on Proprioception

Mechanoreceptors are present in the capsule, menisci, ligaments and a musculature surrounding the knee joint[65–67,93]. Current proprioception tests cannot discriminate between loss of afferent

signals due to an ACL injury or altered activity in the remaining receptors[104]. Although several tests for knee proprioception have been reported in the literature, no consensus or gold standard of assessment has been established[105]. Threshold to detection of passive motion (TTDPM) and joint position sense (JPS) are two of the most commonly used methods to assess the afferent aspects of joint proprioception[106]. Emerging tests to assess alterations in cortical processing and neuroplasticity components of proprioception include electroencephalography (EEG)[107], somatosensory evoked potentials (SEP)[108], functional MRI (fMRI)[109] and neurocognitive assessment tools (IMPACT)[110]. The efferent aspect of proprioception, or neuromuscular response, is often assessed by kinematic assessments and electromyographic (EMG) activity[106]. Caution should be used when comparing the results of knee proprioception studies using different methods of assessment[94].

Mechanoreceptors

The atypical mechanoreceptors, which have only been found in ACL remnant stumps following injury, are evidence that degeneration of mechanoreceptors occurs with an ACL injury [78,111–114]. Although some investigations have found the presence of mechanoreceptors in the remnant ACL stump up to 3 years post-injury, it is believed the length of time from injury correlates with a decrease in the number of mechanoreceptors[78]. The remaining mechanoreceptors located in intact structures, primarily the muscles, must adapt to the lack of information from the ACL. Dynamic stability is best achieved if a patient is able to compensate via the proprioceptive information provided from the mechanoreceptor of the muscles, and other structures (copers). If they are unable to adapt (non-coper) the knee will remain unstable[94,103]. Input from mechanoreceptors in all the various knee structures provides the CNS with the necessary proprioceptive information. However, the contribution of each type of receptor and its anatomical location is still unknown[105]. It is possible that the impact of an ACL injury on knee

proprioception is minimal, as only 1-2.5% of the total area of the ACL is made up of mechanoreceptors[65,66]. It could be argued that the afferent proprioceptive information from the muscles is more significant than those obtained from the ACL[94,106,115]. Although it is controversial, it may explain why some individuals are more susceptible to ACL injury and why regardless of management strategies (conservative rehabilitation or reconstruction) some patients with an ACL injury are able to return to their previous level of activity, while others continue to have functional deficits[94,105,106].

CNS Pathway

Numerous studies have investigated the effect of ACL injury on the afferent component of proprioception via the TTDPM and JPS methods. TTDPM assesses joint kinaesthesia by having a subject indicate the first instance they perceive motion of the joint. It is thought to measure the responses of rapid receptors such as the Pacinian corpules, while the slower response of ruffini nerve endings and GTOs are assessed with JPS measurements[94,105,116,117]. JPS involves passively moving a joint to a target angle, and then asking a subject to actively reproduce the angle. TTDPM methodologic studies show a definite decrease in joint proprioception, when compared to the uninjured limb (internal control), and in comparison to healthy individuals (external controls)[102,117–121]. Investigations utilizing the JPS technique have reported conflicting results that are likely attributable to the type of control group used for the investigation. When using an internal control in which the same subject's affected and unaffected limbs are compared, several investigations have reported no difference in proprioception, while others have found deficits in proprioception[100,118,122]. In contrast, when a healthy individual serves as the (external) control, the ACL deficient subjects consistently demonstrate decreased proprioception via JPS tests[120,123]. It has been suggested that bilateral deficits in proprioception may pre-exist in individuals or may develop following an ACL injury, resulting in the contralateral limb not being a suitable

control[76,105,107]. Overall, the TTDPM and JPS tests indicate that patients with an ACL injury tend to have decreased proprioception[94].

Changes to the cortical areas involved in the processing of the somatosensory sensation of proprioception demonstrate that an ACL injury is more complex than a simple peripheral musculoskeletal impairment[107,109]. EEG and SEP techniques have been used to monitor cortical brain activity. Investigations using EEG indicate changes in the frontal and parietal areas of the cortex in subjects following ACL injury and subsequent reconstruction. The increases in frontal Theta-power and Alpha-2 parietal areas indicate that the JPS and maximal voluntary isometric contraction (MVIC) tasks are more complex and attention-demanding in the ACL-injured subject. A functional network links the frontal and parietal regions of the brain to provide an interface between perception, long-term memory and action. The altered afferent sensory information due to ACL deficiency may not match the expected information from long-term memory in the brain, and may lead to an increased load of the working memory process to create the appropriate muscular activities[107,124]. SEP techniques measure the electrical potentials in the cerebral cortex upon stimulation of a peripheral neuroreceptor. This reflects the activity of proprioceptive fibers that ascending the spinal cord in the dorsal column[108,125]. Direct stimulation of the ACL and the common peroneal nerve indicate a loss of the SEP (P27) when the ACL is ruptured. A loss of the P27 potential represents a reorganization of the CNS above the medial lemniscus due to an ACL deficit[117,122,126,127]. Other investigations indicate a compensation of the cortical areas of the brain following ACL injury. Functional MRI measures the regional blood flow and metabolic changes linked with function-related changes in neural firing. ACL-injured subjects demonstrate decreased activity in several sensorimotor cortical areas and increased activity in the pre-motor, secondary somatosensory (including the thalamus & cerebellum) and

visual-spatial (lingual gyrus) areas[128]. This indicates that compared to healthy controls, those with ACL injury found the same flexion-extension task to be more complex and required more motor planning. An abundance in sensory information in the visual cortex indicates ACL-injured rely more on visualization and feedback of motion in the absence of proprioceptive information from mechanorecptors[109,128]. The Immediate Post-Concussion Assessment and Cognitive Testing (IMPACT) software is a neurocognitive method of assessing subtle changes in cerebral and cortical function associated with concussion. A recent study indicated that ACL-injured athletes demonstrated significantly slower reaction time, processing speed and performed worse on visual and verbal memory composite scores when compared to healthy controls due to a loss of NM control, mistakes in coordination and spatial disorientation[110]. Further investigations are warranted to determine if an alternate application for this neurocognitive test may be to provide insight into cerebral mechanisms of neuromuscular control and injuries[110].

Neuromuscular Response

When the passive restraint system is compromised by an ACL injury, the dynamic neuromuscular system needs to adapt to prevent an anterior subluxation of the tibia on the femur[83]. While the majority of individuals who injury their ACL will experience the same amount of mechanical instability, their functional outcomes can be drastically different[106]. These differences in function have been attributed to their ability to dynamically control the excessive tibial translation associated with an ACL injury via muscle activation[102,103]. There are distinct difference in the kinematic and kinetic movement patterns of copers and non-copers versus healthy controls. Although they are not normal, the movement strategies adopted by copers have more similarities to healthy controls than the non-copers[103,129–137]. During a unilateral stance, the knees of non- copers are flexed more than the copers and healthy controls[103,137]. In response to a perturbation, copers and healthy controls sequentially activate their hamstrings followed by their

quadriceps. The non-copers demonstrated an asynchronous pattern of activation (medial hamstrings – quadriceps-lateral hamstrings) which potentially creates an internal rotation of tibia, and could be destabilizing in an ACL-injured knee[103]. However, in an attempt to dynamically stabilize the joint both copers and non-copers demonstrate increased co-contraction of the quadriceps and hamstring muscles as compared to healthy controls. This strategy "stiffens" the knee but may also decrease shock absorption and increase the compressive and shear forces on the articular cartilage, which may lead to the development of osteoarthritis that is commonly experienced by ACL-injured individuals[103,137]. Investigations of knee flexion angles at heel strike of gait during walking and jogging also indicate that copers resemble healthy controls, while non-copers had obvious alterations. An altered knee position and a decreased knee extensor moment were thought to indicate a weakness of the quadriceps muscles, 'quadriceps avoidance gait' [130,131,134]. However, there are conflicting reports on the different roles of the quadriceps between copers and non-copers. Some studies have found quadriceps atrophy or weakness is responsible for the compromised gait pattern of non-copers[130,135], while others believe that the altered gait patterns are due to different recruitment and activation of the quadriceps in non-copers[133,136,138]. It has been suggested that the decreased knee extensor moment seen in both copers and non-coper may more likely reflect a greater relative contribution of the hamstrings (flexors) rather than weakness of the quadriceps muscles[138].

Both non-copers and copers have decreased mechanical stability of the knee joint due to a rupture of the ACL. Therefore, the subjective feeling of instability (giving-way) which is frequently experienced only by non-copers cannot be associated with the increased knee joint laxity that both groups exhibit. The symptoms of giving way have been found to be closely associated with altered stretch reflex excitability. A longer latency of the hamstrings in response

to an anterior tibial translation is found in non-copers[139]. Investigations of the efferent aspect of proprioception have focussed on this neuromuscular response of the hamstring muscles to an anterior tibial translation stress. Both the timing of the response and muscular recruitment order are impacted by ACL injury[83,106]. The latency of reflexive hamstring contractions in ACL-injured subjects has been found to be almost twice that of the uninvolved, contralateral limb[106]. Slower spinal cord and cortical level responses to anterior tibial translation were also noted when compared to both the uninvolved extremity and healthy controls. ACL-injured subjects identified as copers had a voluntary recruitment order similar to healthy subjects, hamstrings-quadriceps-gastrocemius muscles. Conversely, the non-coper ACL-injured subjects would initially recruit the ACL antagonist quadriceps muscles[83]. The alteration in the hamstring reflex in the ACL-injured is thought to take place at the spinal level, which can be influenced by sensorimotor training. Rehabilitation exercises that focus on the neuromuscular response early after ACL rupture may be an effective technique to restore normal knee joint function[28,29,139].

ACL Injury and Additional Joint Lesions

In an attempt to maintain joint stability in an ACL-deficient knee other structures are placed under greater stress to restrict anterior tibial translation and internal rotation associated with knee joint laxity. As a result, adolescents with prolonged ACL deficiency are at considerable risk of injury to other structures of the knee: they have a 4-fold increase in the occurrence of meniscal injuries[5], an 11-fold increase in chondral lesions,[5] and are highly susceptible to the early onset of the knee osteoarthritis, with more than 50% of patients developing knee osteoarthritis (OA) within 20 years of their initial injury[10].

An isolated ACL injury typically occurs from a non-contact mechanism, when the knee is close to full extension during a sharp deceleration or pivoting manoeuver[84]. The less frequently

observed ACL-MCL combined injury primarily results from a contact mechanism, when a valgus stress and combined tibial external rotation occur by contact or collision during sports[140]. In an ACL-deficient knee, animal and cadaveric studies indicate that the MCL sustains a pattern of early and more intense strain during anterior tibial translation[141,142]. Lateral meniscal injuries, medial meniscal injuries and chondral lesions frequently occur concomitantly in both isolated ACL and ACL-MCL combined injuries[140]. For athletically active individuals, management of a combined ACL-MCL injury typically follows non-operative treatment of the MCL with delayed surgical reconstruction of the ACL[143].

The medial and lateral menisci provide critical secondary stabilization to an ACL-deficient knee. The 'wedge effect' of the posterior horn of the medial meniscus restrains anterior-posterior displacement, while the lateral meniscus provides restraint to the axial and rotatory loads often applied during sporting activities[54]. Peripheral tears of the posterior horn of the medial meniscus that involve the meniscocapsular attachments or red-red zone that commonly occur in conjunction with contact ACL injuries are termed *ramp lesions*[144]. ACL-deficient adolescents have increased risks of secondary meniscal and chondral injuries when the time from injury to surgical reconstruction is prolonged[5–7]. ACL-deficiency leads to kinematic and contact mechanism changes which significantly increase the contact stress in the posterior-central region of the medial tibial plateau[95]. The management of the meniscal lesions during ACL surgical reconstruction is directly associated with the development of secondary degenerative changes. When meniscectomy procedures are performed there is a dramatically increased risk for developing OA, 3.54-fold increase[145,146]. Thus, the preservation of the meniscus is important to maintain knee joint stability, and prevent the development of debilitating degenerative changes.

Recently, the role of the anterolateral complex to assist the ACL in controlling rotational knee stability has been of interest. The anterolateral complex includes the superficial and deep iliotibial band (ITB), the capsule-osseous layer of the ITB and the anterolateral ligament (ALL), which can also be referred to as a thickening of the anterolateral capsule[147–149]. The anterolateral complex resists tibial internal rotation at increased knee flexion angles, but provides only minimal restraint to anterior-posterior loads[148]. Concomitant ACL and anterior lateral complex injury should be suspected in patients with chronic ACL tears and high-grade pivot-shift test results[148]. Investigations of surgical techniques to effectively manage ACL injuries with associated anterolateral complex deficits are inconclusive and ongoing.

Anterior Cruciate Ligament Injury in Adolescent Females

Incidence Rates

While an ACL injury is a significant risk for both sexes, adolescent females between the ages of 14-18 are the most at-risk with a peak incidence rate of 227.6 per 100,000[2]. Adolescent females are 2-6 times more likely to sustain an ACL rupture than their male counterparts[3,4,13]. In recent years, there has been a dramatic rise in the number of ACL injuries in females, which is often attributed to the combination of the susceptibility due to etiological factors and the drastic increase in female sport participation since the inception of Title IX in the United States[150]. Interestingly, a corresponding differences in the risk of ACL injury and neuromuscular development between males and females becomes apparent after the onset of puberty, sex-related differences are not noted in pre-pubertal athletes[151–153]. Through adolescence it is common for individuals to experience delays or regressions in neuromuscular function[154,155]. However, females lack the increase in power, strength and coordination (neuromuscular spurt) that males experience during puberty[154,156].

Etiological Factors

Three major etiological contributors to the post-pubertal gender disparities between ACL injury have been identified as anatomical, hormonal and neuromuscular factors[35,49,157–161]. Investigations regarding the influence of sex-related anatomical factors and the rate of ACL injury are inconsistent[162]. Although the risk of ACL injury is increased in individuals with intercondylar notch stenosis, there is no difference in the sex of the injured athletes[163]. Conversely, a higher proportion of females have an A-shaped notch, one which narrows from the base to the apex, but notch shape and sex do not correlate with injury rate[164]. An increased posterior tibial slope of the knee joint results in an anterior translation of the tibia, from the compressive load of the tibiofemoral joint and the superior pull of the quadriceps muscle, placing greater strain on the ACL[162]. Studies have found that ACL-injured females have a significantly greater posterior tibial slope compared to healthy females[165–168]. While no association between slope and injury status has been noted between males and females[169,170]. However, a recent report found that the relationship between a combination of knee geometry factors and risk of ACL injury were different between males and females. Females with a decreased femoral notch width and an increase posterior tibial slope were most at-risk of sustaining an ACL injury, while in males it was a combination of decreased ACL volume and decreased posterior meniscus angle[171]. Additionally, joint laxity and genetics are possible contributors to the increased ACL risk in adolescent females. Higher generalized joint laxity has been found in post-pubertal females compared to males[172]. Limited reports in the literature indicate that inheritable collagen disorders such as Ehlers Danlos and Marfan's syndrome, as well as genetics, may also influence laxity[173,174]. However, studies indicate that it's the ability of surrounding musculature and other structures that determine functional stability of the knee joint[102], rather than knee joint

laxity[94,175,176]. While it is important to note that anatomical factors may contribute to the ACL risk factor for adolescent females, they are essentially unmodifiable.

Hormonal factors associated with the menstrual cycle have also been suggested as a contributor to the increased risk of ACL injuries in adolescent females. Increased knee laxity and ACL injury has been linked to hormonal fluctuations associated with the follicular and ovulatory stages[177–181]. Post-pubertal females maybe the most at risk during the pre-ovulatory phase of the cycle, with changes in joint laxity occurring during the ovulatory phase[177]. With limited investigations, the role of oral contraceptives to stabilize hormonal levels remains uncertain[178,181]. Conversely, the menstrual cycle and oral contraceptives were found to have no effect on knee or hip joint loading, dismissing the influence of hormonal factors on ACL injury rates[182]. Thus the influence of hormonal factors on ACL injuries in adolescent females requires further investigation, and may also be unmodifiable.

Recently, the focus of literature has been on the modifiable factor of neuromuscular control deficits in adolescent females which may increase their risk of ACL injury. Neuromuscular control deficits are defined as muscle strength, power or activation patterns that lead to increased knee joint and ACL loads[183]. Four potential neuromuscular deficits have been identified in adolescent females: 1. Ligament dominance; 2. Quadriceps dominance; 3. Leg dominance; and 4. Core dysfunction dominance[157,183].

1. Ligament dominance

"Ligament dominance" is the imbalance between the neuromuscular and ligamentous control of dynamic knee joint stability. Individuals with this deficiency have an inability to control lower extremity frontal plane motion during landing and cutting maneuvers[183]. Visually they have a knock-kneed or "valgus" knee position when performing dynamic tasks[157]. A screening protocol found that females who sustained ACL injuries had knee

abduction angles eight degrees greater and knee abduction moments 2.5 times greater than uninjured females[158]. This has also been linked to altered hip recruitment strategies, with females demonstrating significantly greater hip moments, higher knee to hip ratios, decreased gluteus maximus activation, and greater hip adduction angles compared to males[184–187].

2. Quadriceps Dominance

"Quadriceps dominance" is an imbalance between the strength, recruitment and coordination of the quadriceps (knee extensor) and hamstring (knee flexor) muscles[183]. Females with decreased hamstring strength and relatively similar quadriceps strength compared to males were more likely to suffer an ACL injury, than those with decreased quadriceps and similar hamstring strength[188]. Additionally, female athletes tend to preferentially activate their quadriceps relative to the hamstrings, limiting their ability to dynamically stabilize the knee joint[189,190]. These athletes tend to land with small knee flexion angles and a flat foot position[157]. In addition to the previously mentioned increased knee valgus (abduction) moments[158], females also demonstrate decreased hamstring/quadriceps ratios[189].

3. Leg Dominance

"Leg dominance" is characterized by an imbalance between the strength, coordination and control of the lower extremities[183]. ACL-injured females demonstrate significant side-to-side differences in dynamic knee valgus, compared to healthy females[191]. Furthermore, side-to-side limb asymmetries can be a predictor of ACL injury risk in healthy females[13], and future secondary ACL injury in previously reconstructed limbs[159]. These athletes may have unequal thigh height during a jump, non-parallel foot placement when landing or unequal foot contact time[157].

4. Core Dysfunction Dominance

"Core dysfunction dominance" refers to an imbalance between the inertial demands of the trunk and core control and coordination to resist it[183]. Trunk motion and lower extremity positioning can be modulated by the pre-activation of the core (Transverse Abdominis and Oblique Abdominal) and hip stabilizer muscles[192–194]. Thus, decreased core stability can predispose individuals to lower extremity injuries, and is particularly evident in female athletes compared to males[13,195]. Athletes with core dysfunction may have nonparallel thighs at the peak of a jump, pause between consecutive jumps and/or not land in the same footprint[157].

These neuromuscular control deficits are the only modifiable factors. As such, they are of particular interest to therapeutic rehabilitation clinicians, and have been the focus of many investigations to reduce the rate of ACL injuries in this at-risk adolescent female population[28–30,32].

2.5 Neuromuscular Exercise Interventions

Preventative Neuromuscular Training

Preventative neuromuscular training is recommended for all young athletes to reduce costs and morbidity from ACL injury[196]. In addition to reducing the rate of ACL ruptures in females adolescents by approximately 50%[29,30,32,197], incorporating preventative neuromuscular training during early adolescence can improve lower extremity performance[31,198–202]. The objective of neuromuscular training is to improve dynamic joint stability, generate fast and optimal muscle activation and decrease joint forces. Variability among neuromuscular exercise interventions is wide, with programs often incorporating different components of training such as strength,

proprioception, balance, gait re-education, plyometrics and functional performance[29–32,197,198,203–208]. While a combination of exercises is recommended, this makes it difficult to conclude which component(s) are the most effective risk factor modifiers[204,207,209,210]. The frequency, duration and timing of training; how the program is conducted, supervised or unsupervised; participant compliance; age and gender of participants are all important variables that can influence outcome measures and injury rate reduction[197,207,211–213].

Combination Neuromuscular Exercise Programs

A recent systematic review of the ACL injury prevention literature suggested that a neuromuscular training program for females athletes should include a combination of strength training, plyometrics, balance training with technique monitoring feedback[203]. Furthermore, the authors recommend that neuromuscular training should be a minimum of 6 weeks in duration during the preseason, with a reduction to 1-2 sessions per week during the season to be effective. Additional sport specific maneuvers such as agility drills or jump training are also beneficial and address the functional biomechanical demands of each sport[203]. Research also indicates that multi-faceted, short duration neuromuscular training programs that incorporate plyometric and dynamic movement, core strengthening and balance, and resistance training also improved measures of performance and movement biomechanics in adolescent females[198,214]. Supervised training of three 90-min sessions a week for 6 weeks resulted in significantly improved single-leg postural stability, predicted 1-rep maximum squat, vertical jump and sprint speed in young female athletes[198,214]. Similarly, an 8-week neuromuscular training program combining core stability, plyometric and body-weight strengthening resulted in improved dynamic balance ability of elite junior skiing athletes[199], elite female basketball players[202] and adolescent female soccer players[200,201].

Isolated Neuromuscular Exercise Programs

While the literature supports the notion that ACL injury prevention programs which combine several neuromuscular exercise components are effective, these programs can be lengthy in duration and hinder participant compliance. Investigations into which components in isolation can promote similar beneficial changes in adolescent females are required. Studies which paired body-weight resistance training with both isolated core stability/balance (BAL) and plyometric (PLYO) components were effective at increasing measures of lower extremity strength (isokinetic hamstring, squat and hang clean), power (vertical jump) and control (center of pressure during hop landing), as well as decreasing side-to-side leg asymmetries[215]. Beyond this, the BAL group also significantly reduced impact landing forces when landing from a single-leg hop, while the PLYO group had no effect on force attenuation strategies[215]. Another study investigated the effects of a BAL, PLYO or standard combination neuromuscular (NM) program on lower limb biomechanics of adolescent female athletes[216]. Both the PLYO and NM groups displayed significantly greater peak knee flexion angles when landing, placing participants in a biomechanical position which may reduce ACL injury risk[216]. Interestingly, none of the training affected frontal plane knee postures (valgus) which is an ACL injury risk factor. However, the PLYO group did decrease hip adduction positioning which may subsequently decrease knee valgus collapse[216]. Although the isolated types of training showed beneficial results, investigators recommend that the effectiveness of neuromuscular ACL prevention training programs may be maximized by using a combination of exercise components[215,216]. Finally, a targeted neuromuscular training program (CORE) that consisted of integrated trunk and hip exercises, and was designed to improve the ability to control the trunk and improve core stability during dynamic activities[217], indicated that this progressive program improved hip abduction strength[218] and lowers knee injury incidences in female high school athletes[219]. These results

suggest that a focussed neuromuscular exercise program that is time efficient (20 mins) and conducive to a team-based approach can have beneficial results on the biomechanical risk factors and ACL incidence rates for adolescent females.

Warm-up Based Soccer Neuromuscular Programs

Adolescent females are most at-risk of ACL injury when participating in soccer (12.2 ACL injuries per 100,000)[220]. Thus, soccer specific warm-up based neuromuscular intervention programs have been developed, and investigated in the adolescent female population. The HarmoKnee prevention program that incorporated muscle activation, balance, strength and core stability components in a 20-25 min warm-up conducted over the pre-season and regular season of a community-based soccer program demonstrated a 77% reduction in knee injuries, including a 90% reduction in non-contact mechanism knee injury in adolescent females[221]. Another neuromuscular warm-up program (Knäkontroll, SISU Idrottsbőcker, Sweden, 2005) consists of six exercises; 1-legged squat, pelvic tilt, 2-legged squat, bench, lunge, jump/landing techniques[222]. Studies have shown that this program can result in a 64-88% reduction in the rate of ACL injuries in adolescent females, with greater injury rate reductions with high-compliance of the program[211,223]. However, the most popular warm-up based neuromuscular prevention program is the FIFA 11+ program[224]. The FIFA 11+ programme is a 20 min warm-up consisting of 15 exercises, divided into 3 parts: running with a focus on cutting, jumping and landing (parts 1 & 3); and strength, plyometrics, agility and field balance components (part 2). Unfortunately, low compliance with this program was thought to be the reason why no difference in the overall rate or type of knee injury was observed in an Norwegian cluster-randomized control study[225]. In contrast, a Canadian cluster-randomized study found a significantly lower injury rate and improved dynamic balance performance in the group that received on-field supervision of the program compared to the unsupervised group[226]. Additional investigations confirm the results of

the Canadian investigation and found that the FIFA 11+ program produces improvements in physical performance such as dynamic balance, agility drills, vertical jump height, drop jump and horizontal jump distance which could potentially contribute to injury risk reductions. These results are promising and suggest that neuromuscular prevention programs are effective, but also highlight the need for direct supervision of participants.

Pre-operative Rehabilitation Interventions

In North America, the standard of care for patients following ACL injury is surgical reconstruction[14,15]. Early surgery is especially favoured for adolescents vs. non-operative or delayed treatment, as it restores joint stability and promotes return to previous levels of physical activity[227]. However, skeletal immaturity[15,17] and long surgical wait times[16] can both result in a significant delay between ACL injury and surgical reconstruction. Patients awaiting surgery are recommended to participate in short-term, progressive exercise programs as there is evidence to suggest that they can improve knee function[208]. Unfortunately, exercises such as plyometric single-leg hops, jumps, pivoting and cutting maneuvers that are often incorporated in neuromuscular prevention programs may not be the most appropriate for ACL-injured patients. Especially since ACL-injured individuals have a high level of kinesiophobia - a fear of movement and re-injury[228]. Thus alternative perturbation-based NM programs have been developed to address the specific needs of ACL-injured adults[18,19,21,22,24,229,230]. However, currently no research has investigated the effectiveness of this type of training in the at-risk adolescent female population.

Standard Pre-operative Programs

A range of approaches are often used within standard pre-operative ACL rehabilitation programs. They often include exercises to address one or more of the following aspects of

training: range of motion, strength, proprioception/balance, gait re-education, and functional performance[23,208,231–235]. Studies of ACL-injured active young adults have found that standard pre-operative rehabilitation programs are able to improve patient-reported knee-related function scores (Lysholm[231,232], Knee Injury and Osteoarthritis Outcome Scoring (KOOS)[232–235] and modified Cincinnati[23] scoring), as well as measureable outcomes such as proprioception (reflex hamstring contraction latency[231]), quadriceps strength[232], movement pattern and flexion angle during gait[232] and single-legged hop tests[23]. However, most subjects are unable to return to pre-injury activity levels, as demonstrated by decreased Tegner scores[232–235]. While evidence supports pre-habilitation as a primary treatment option following acute ACL injury or for those awaiting surgical reconstruction[23,208,235], further research is warranted to determine the optimal type of exercises, frequency of sessions, program duration and mode of delivery. One study has reported that a proprioception-based closed-kinetic chain (CKC) program was more effective than a traditional strength-based closed-kinetic chain (OKC) program[231], while another found contrasting results as a comprehensive rehabilitation program with OKC quadriceps exercises produced significantly greater strength gains than a similar program with CKC exercises[232]. The frequency of sessions has ranged from 2-4 per week, with a range of 3-24 weeks for the duration of the program[23,231–235]. Programs also differ in their mode of delivery, and ranged from a circuit-based class[231], sessions directly supervised by a therapist[23,233–235], as well as an unsupervised home-based program[232].

Perturbation-based Neuromuscular Pre-operative Program

Perturbation-based neuromuscular training was developed to be safe and effective pre-operative programming for the ACL-injured, physically active population[33]. It includes exercises in which the patient maintains balance on a support surface while a clinician deliberately perturbs (i.e.,

manipulates) the support system[20]. It is a 5-week program in which participants complete a total of 10 supervised sessions, two sessions per week[18–27]. In brief, a series of destabilizing perturbations are applied to each of the involved and uninvolved legs during stance on each of three unstable surfaces (rockerboard, rollerboard and rollerboard/platform), both in bilateral and unilateral stance[33]. Over the course of the program, application of the destabilizing force progresses from an informed unilateral direction, slow and low in magnitude, to an unexpected, rapid application of destabilizing forces in random directions with sport-related distractions (a ball toss). To encourage selective muscle activation from patients, rather than a strong co-contraction response of the lower extremity musculature, patients are instructed to match, not overcome, the therapist's perturbation forces[33].

Most published reports have focused on the effects of standard programs supplemented with perturbation-based NM training on kinematics and gait mechanics. They have reported that perturbation training improves knee kinematics and movement patterns in a physically active adult population[21,22,24,229,230,236,237]. Additionally, patients who completed a perturbation-based program were almost 5 times more likely to successfully return to high-level physical activity, and maintain their functional status for longer periods than those who completed only a standard program[20]. Pre-operative perturbation training also resulted in better pre-operative Knee Injury and Osteoarthritis Outcome Scores (KOOS), especially on the pain, activities of daily living and sports and quality of life subsections[19]. Performance based effects have also be reported, as participants of perturbation-based programs have demonstrated changes in quadriceps and hamstring muscular strength[18], and improvements in single and triple hop tests[18,20]. While these results are encouraging, the effects of perturbation-based NM training in isolation remains uncertain and the effects on the at-risk adolescent female population is still unknown.

Impact of Neuromuscular Exercise Training on Proprioception

The goal of neuromuscular exercises is to activate motor-response sequences that occur prior to and during stressful knee joint loading situations. Training programs incorporate the concept of feed-forward processing, in that the neuromuscular system can control fast movement if it has previously encountered the situation[81]. It has been established that dynamic stability is compromised in the ACL-injured individual, especially in those with recurrent giving-way episodes (non-copers). Through exposure to potentially destabilizing loads during training, the knee may be able to develop an effective neuromuscular compensatory pattern to dynamically stabilize the joint. Thus, preventing ACL injury or returning functional stability to an ACL-deficient joint. The effects and underlying mechanism of two similar neuromuscular exercise protocols, perturbation training[33] and sensorimotor training (SMT)[238], have been investigated. Similar to perturbation training, SMT consists of unilateral exercises on wobbling boards, spinning tops, soft mats and two-dimensional free moving platforms. The SMT program volume varied between studies, 8 sessions over a 4-week time period[238–240], 16 sessions over a 4 week period[241,242], or 18 sessions over a 3-week period[243]. The functional and neural adaptations of SMT have been exclusively examined on a healthy population, while research involving perturbation programs has primarily focused on the ACL-injured population. These investigations provide great insight into the role of neuromuscular exercise training on the sensorimotor pathways.

Data suggest that the rate of force development (RFD) is improved following SMT without increasing maximum strength, indicating that neural activation of the motor neurons is effected by this type of training. It has been suggested that SMT influences the proprioceptive afferent components, possibly by withdrawing the presynaptic inhibition of Ia fibres belonging to the

motor neurons of the acting muscles[238]. Following SMT, the response to an anterior tibial translation indicated a reduced tibial displacement and increased joint stiffness via enhanced hamstring activation. This suggests that SMT may have implications for ACL injury prevention[244] and rehabilitation. Facilitation of the afferent ligament-muscle reflex at the spinal level is most likely the mechanism for this observation, although alteration of CNS processing may also contribute to a more efficient regulation of joint stiffness in functional situations[241]. Changes in corticospinal and spinal excitability were further investigated using H-reflex and transcranial magnetic stimulation (TMS). Following training, reduced cortical excitability was related to improved postural stability, suggesting that supraspinal adaptations occurred with SMT[243]. During skill acquisition cortical activity is increased, but with progressive training the motor cortex activity reduces as the task becomes automatic in nature. The decreased cortical activity is typically accompanied by increased activity in the subcortical areas such as the basal ganglia and cerebellum[243].

Several studies have also compared the effects of SMT to high-intensity strength training (HST) in healthy subjects. Although both training methods were found to improve strength, the adaptations of the neuromuscular system are quite different for each exercise[239,240,243]. SMT training is thought to alter the peripheral afferent input on the CNS to optimize regulation of relevant muscles. While HST is suggested to improve the efferent pathway of the system, by improving intramuscular co-activation[239,240]. Thus, it has been suggested that optimum strength gains could be achieved when SMT is completed prior to HST. It was also noted that SMT alone could be useful in strength and power training if extremely high loads cannot be used, such as during adolescent growth periods or following an acute injury[240]. Interestingly, both SMT and HST improved jump performance in adolescent males, but also demonstrated opposing adaptions

on the neuromuscular system. HST enhanced the H-reflex (this increased spinal activity was thought to be an attempt to optimize motor neuron output) while SMT diminished the H-reflex (indicating a decrease in the spinal excitability of the reflex pathways). One possible explanation for these conflicting results is that SMT may have shifted the movement control to supraspinal pathways in order to control the precision of muscular activity[243]. These results suggest that SMT is an effective method to improve neuromuscular control of the healthy knee, and future investigations should target the ACL-injured population.

Early investigations of neuromuscular exercise training on the ACL-injured population used a combination of standing , seated, and kneeling positions with wobble boards[231,245]. These studies indicated that both copers and non-copers improved their muscle reaction times by completing the program. In the non-copers study, hamstring peak torque time significantly decreased, indicating a shortened lag time between neural proprioception and muscle response[245]. While the investigation targeting copers indicated that the reflex hamstring contraction latency (RHCL) significantly improved[231].

Although investigations of perturbation protocols have demonstrated their efficacy in an ACL-injured population (including copers and non-copers), there is still a lack of direct evidence of the neural adaptations that may result from this specific type of training[18,19,24,236,237,246–249]. It has been noted that when a standard rehabilitation program is augmented with perturbation training, the perturbation group has less episodes of giving way [246]. In comparison to pre-training results, research indicates that ACL-injured copers demonstrate higher quadriceps activity (ACL antagonist), without experiencing knee instability following perturbation training. Data indicate that a coupling activation of the hamstring and soleus muscles countered the effects of the quadriceps, creating a dynamically stable knee during walking. It was also suggested the

perturbation training may have modulated the reflex pathways to allow for the formation of this relationship[248]. While copers may have been able to modify the co-contraction of their quadriceps-hamstrings to become more similar to healthy control subjects[247], direct measures of the underlying change to the neuromuscular system are needed to confirm these assumptions. Quadriceps dominance in female athletes has been speculated as a contributing factor to the increased rate of ACL injuries. Studies investigating this neuromuscular imbalance between knee extensor and flexor strength, recruitment and coordination have indicated that perturbation training can mediate this factor. In healthy females, perturbation training was able to modify the time of the ACL agonist muscles (hamstring and gastrocnemius) to contract after heel strike, creating a normal quadriceps-hamstring balance and increasing active knee stiffness[237]. Improved hamstring muscle recruitment in females was able to balance the co-contraction of quadriceps that were activated during a drop-landing and jump-tuck maneuver. Knee-flexion angle during landing also increased following perturbation training, suggesting that the females had adopted a dynamic stabilization strategy, rather than a simple joint stiffening pattern[250]. When assessing non-coper females, perturbation training helped to successfully resolve the pre-training gait abnormalities of reduced hip and knee flexion angles and moments in the injured limb[249]. Current evidence suggests that perturbation training is able to influence the neuromuscular mechanism controlling knee joint stability, but further investigations to examine whether adaptations occur at the levels of spinal reflex and/or supraspinal pathways, are required.

2.6 Clinical Assessment of Dynamic Balance

Currently there is no “gold standard” for measuring balance, as laboratory-based and clinical methods of assessment evaluate different components such as static stability, dynamic stability,

anticipatory postural control and reactive postural control[251]. Thus, it is important to identify which aspect of balance is being evaluated by a test and to choose a balance test that best matches the purpose of testing such as fall risk or athletic performance[34,251].

Clinicians often use dynamic balance tests as a functional screen to identify athletes at-risk of injury, assess deficiencies following injury, and to monitor rehabilitation progress[35]. The Star Excursion Balance Test (SEBT)[36,37] and Y-Balance Test (YBT)[38,39] are two reliable methods commonly used to clinically assess dynamic balance of the lower extremity. Both the SEBT and YBT simultaneously assess range of motion, flexibility, neuromuscular control and strength[40]. Within each test, there are a number of factors that can be reported and analyzed to assess lower extremity injury risk. These include maximal reach distance measured in specific reach directions, a calculated composite score and side-to-side asymmetries. Since measures of clinical performance are influenced by many factors including age, sex, body-mass index (BMI), injury and participation in specific sports, determining normative scores for specific populations is required[43–49]. While the SEBT and YBT are very similar in nature, reach distances and kinematic profiles differ between the tests within a healthy adult population suggesting that the values between tests should not be used interchangeably[41,42]. Additionally, it is recommended that injury risk thresholds or cut-off scores should only be utilized for comparison with the specific test and participant population from which they were developed[252].

Star Excursion Balance Test (SEBT)

First introduced by Gray[253] as a rehabilitative tool, the SEBT is a simple test that uses 8 designated lines taped in a star pattern to the floor at 45° angles to one another. To complete the SEBT, a subject is instructed to maintain a unilateral stance while using the other limb to toe touch a maximal reach distance along the designated lines of the grid pattern[40]. The evaluator

then marks the tape at the spot that the participant touches down. The distance from the center of the grid to the spot on the tape is measured, with further reach distances indicating better dynamic postural control[40,254]. If the subject loses their balance, rests their reaching foot on the ground, makes contact with the ground on the reach or return to bilateral stance to gain balance, or lifts or shifts any part of the stance foot the trial is considered incomplete[254,255]. Reach distances are normalized and expressed as a percentage of limb length, allowing for comparison within and between groups; as well as to quantify deficits or improvements before and after interventions[255].

For research purposes, a standard testing sequence is often followed (either clockwise or counter clockwise) with the average of three test trials reported for each reach direction[254].

Initial testing can be quite time consuming, as each limb of a subject will perform a total of 9 trials (6 practice and 3 test) for each of the 8-reach directions. Research indicates that normalized reach excursion distances will stabilize after 4 practice trials, thus the recommended number of practices trials was reduced from 6 to 4[256,257]. Similarly, to reduce the length of time to perform the test without compromising validity, the utilization of all 8-reach directions is often modified (mSEBT) to only 3-reach directions: Anterior (ANT), Posteromedial (PM) and Posterolateral (PL)[256,258,259]. A composite score, which is the sum of the ANT, PM and PL reach directions divided by 3 times the limb length, then multiplying by 100, is often reported[49]. However, recent evidence suggests that specific reach directions of the mSEBT correlate with specific lower extremity impairments, and thus are important to report[43,47,258,260,261]. Side-to-side asymmetry in the anterior reach direction has been found to be an important measure, as it can assist in identifying athletes at-risk of sustaining a lower extremity injury[47,252].

Validity testing of the SEBT is limited, and challenging due to the fact that balance tests often assess different sub-types of postural stability[34,251]. A laboratory-based postural stability test is the Biodex Balance System (BBS), which consists of a mobile platform that tilts in all directions and oscillates in the anteroposterior, mediolateral and overall directions simultaneously[262]. The BBS and SEBT were determined to measure the balance components of underlying motor systems, functional stability limits and anticipatory postural control, while the SEBT also measures static stability[251]. Although both tests are expected to measure similar aspects of balance, no systematic or consistent relationship was found between the BBS limits of stability (LOS) test and the SEBT in healthy university students. This indicates that the tests may actually assess different components of balance[34]. Hop testing is a reliable and valid performance-based measure often used for assessing ACL- deficient patients and those undergoing rehabilitation following ACL reconstruction[263,264]. However, it is not always suitable for use in patients with a lack confidence or muscular strength deficits due to injury[265].

The One Leg Hop for Distance – single hop (OLHD) is a performance test used to assess the ability of the neuromuscular system to dynamically stabilize the knee joint. Participants jump on one leg as far as they can, landing on the same leg and stabilizing for at least 2 seconds[265]. Construct validity has been established for the PM and PL reach directions of the SEBT, but not for the anterior reach direction or the composite score in recreationally active healthy and ACL-injured adults[265].

For a healthy adult population, the intra-rater reliability of the SEBT has been reported as moderate to good with intraclass correlation coefficients (ICCs) ranging from 0.67 to 0.97[37,257,266] and poor to good inter-rater reliability with ICCs 0.35 to 0.93 ICCs[266]. There is limited data in the literature assessing ACL-injured[35,267] or ACL reconstructed adults[268,269].

Normative scores for the SEBT in an adolescent population are limited to normalized scores for only the posteromedial direction[270], elite male junior rugby union players and high-school basketball players of both sexes[47]. The mSEBT was found to be a reliable measure of dynamic balance for the adolescent basketball population, with intra-rater ICCs ranging from 0.82 to 0.87 and coefficients of variation ranging from 2.0% to 2.9%[47]. To our knowledge, there is an absence of data regarding normative scores on the SEBT or mSEBT for recreationally active healthy or ACL-injured adolescent females.

Y-Balance Test (YBT)

The commercially available YBT is an instrumented version of the mSEBT, designed to improve repeatability and standardize test procedures[38]. Subjects maintain a one-legged stance on an elevated stance platform from which three pieces of plastic pipe extend in the specific ANT, PM and PL directions. With the non-stance foot, participants push an indicator to a maximum distance along the pipe, marked with 0.5 cm increments. Similar to the mSEBT, subjects perform 4 practice trials in each direction before completing the 3 test trials. Tests are conducted with a standardized order of ANT, PM and PL, then repeated in the same order for the other limb. If a subject kicks the reach-indicator plate to gain more distance, makes contact with the ground on the reach or return to bilateral stance in order to regain balance, or lifts/shifts any part of the stance foot, the trial is considered incomplete, and is repeated. The distance from the YBT apex of the most proximal edge of the reach indicator is recorded. All reach distances are normalized as a percentage of each participant's stance-limb length (%LL) – which is determined by measuring from the anterior superior iliac spine to the most distal aspect of the ipsilateral medial malleolus in a supine, lying position[36]. Similar to the SEBT, research suggests that performance

on the YBT varies greatly based on age, gender, injury history, sport participation, competition level, and even nationality[44,271–275].

Validity testing of the YBT is also limited within the literature, yet demonstrates similar results as the SEBT in regards to the BBS and hop testing. The BBS has also been used to assess the validity of the YBT in a recreationally active adult (18-40 years of age) population. Poor validity has been noted between the Stability Index of the BBS (SI-BBS) and YBT in individuals with and without a history of lower extremity injury - no correlations were found between the tests[276]. Alternatively, anterior reach symmetry for the YBT was associated with triple hop distance (THD) and single hop distance (SHD) testing at return to sport in ACL-reconstructed adults[277]. Additionally, the YBT appears to be a valid test in the assessment of fall risk in older adults (≥ 65 years of age). Correlations were found between the YBT and several performance-based tests (30-second chair stand , 8-foot up and go, timed up and go, single-leg stance test) when assessing the risk of falling in an older adults. Thus, as noted previously careful consideration of the purpose of the test (athletic performance or fall risk) should be considered when assessing the validity of different balance tests[34,251].

For an adult population, excellent intra-rater reliability was achieved for a male collegiate soccer player population[38], while only fair to good reliability (ICCs less than 0.74) were found for adolescent male semi-professional soccer players. Interestingly, excellent inter-rater reliability for within session (ICCs greater than 0.99) and between session (ICCs 0.907 to 0.974) comparisons have been reported in children[48]. Research indicates that male and female adolescents with surgically reconstructed ACL's demonstrate deficits in YBT performance at 3 months[277] and 9 months post-operatively[278]. However, normative YBT scores specific to

recreationally active healthy and ACL-injured adolescent females does not currently exist in the literature.

3. Global Thesis Details

3.1 Purpose

The purpose of this research project was to use an evidence-based approach to investigate clinical dynamic balance testing and perturbation-based neuromuscular exercise training in healthy and ACL-injured adolescent females. The results are expected to provide researchers and clinicians with information which could potentially advance the current standard of care used in the prevention and pre-operative management of ACL-injured adolescent females. The central hypothesis was that 1) Clinical dynamic balance testing can be used to effectively assess and differentiate between healthy and ACL-injured adolescent females; 2) Perturbation-based NM exercise is a safe and effective training technique, and can be used to improve dynamic balance and knee joint function in adolescent females.

3.2 Aims and Objectives

The research project was divided into four distinct sections in order to examine specific components of clinical dynamic balance tests and the effects of the perturbation-based neuromuscular exercise program on lower limb outcome measures in adolescent females.
The objective of the first portion of the thesis (Chapter 2) was to investigate the relationship between performances on two commonly used clinical dynamic balance tests in an adolescent female population. The hypothesis was that: 1) Measured reach distances for three common directions; 2) A calculated composite score; and 3) Side-to-side limb asymmetry for the ANT

reach distance would differ between the mSEBT and YBT for physically active adolescent females. Specifically this portion of my PhD research project had the following aims:

- To quantify the measured reach distances for the mSEBT and YBT in adolescent females.
- To calculated composite scores for the mSEBT and YBT in adolescent females.
- To determine side-to-side limb asymmetry in the anterior reach direction for the mSEBT and YBT in adolescent females.
- To compare the various outcome scores from mSEBT and YBT testing completed on adolescent females.

The objective of the second portion of my thesis (Chapter 3) was to investigate YBT reach distances and the association to anthropometrics, lower limb variables and performance on the YBT in healthy and ACL-injured adolescent females. The hypothesis was that: 1) There would be differences in the YBT reach distances in healthy and ACL-injured; 2) YBT performance would be associated with anthropometric characteristics and lower limb physical parameters for both groups. The specific aims of this portion of the investigation were:

- To record anthropometric characteristics of height, weight and BMI in healthy and ACL-injured adolescent females.
- To measure lower extremity variables of proprioception, range of motion, flexibility, and strength in healthy and ACL-injured adolescent females.
- To measure YBT performance in healthy and ACL-injured adolescent females.
- To investigate the relationship between anthropometric characteristics and YBT performance in healthy and ACL-injured adolescent females.
- To investigate the relationship between lower extremity variables and YBT performance in healthy and ACL-injured adolescent females.

The objective of the third portion of this research project (Chapter 4) was to perform a kinematic assessment of the knee and ankle joint function during execution of the anterior reach direction of the YBT in healthy and ACL-injured adolescent females. The hypothesis was that: 1) Healthy and ACL-injured adolescent females would differ in their anterior reach distances; and 2) YBT reach distance would be influenced by kinematic profiles and movement strategies. Specifically, the aims of this portion of the investigation were:

- To quantify the reach distance of physically active adolescent females when performing the anterior reach of the YBT.
- To quantify the degree of knee joint flexion, ankle joint dorsiflexion, and knee joint valgus when performing the anterior reach of the YBT.
- To examine the relationship between knee and ankle joint kinematics and scoring for the anterior reach of the YBT.
- To compare the kinematic data and anterior reach scoring on the YBT between healthy and ACL-injured adolescent females.

The final portion of this research project (Chapter 5) investigated the effectiveness of a perturbation-based neuromuscular exercise program on dynamic balance, lower limb proprioception, flexibility and strength in healthy and ACL-injured adolescent females. The hypothesis of this investigation was that completion of a perturbation-based neuromuscular exercise program would improve: 1) YBT reach distance scoring; and 2) Lower extremity physical measures such as strength, proprioception and flexibility in healthy and ACL-injured adolescent females. Specifically, the aims of this portion of the investigation were:

- To determine if there was a difference in YBT performance following completion of a perturbation-based neuromuscular exercise program.

- To determine if there was a difference in knee proprioception following completion of a perturbation-based neuromuscular exercise program.
- To determine if there was a difference in flexibility of the hip or ankle joints following completion of a perturbation-based neuromuscular exercise program.
- To determine if there was a difference in knee flexion, knee extension, hip internal rotation, hip abduction or ankle dorsiflexion strength following completion of a perturbation-based neuromuscular exercise program.

3.3 Data Analysis

Traditionally research is evaluated using statistical methods to accept or reject a hypothesis, based on probability[279]. Most often T-tests and analyses of variance (ANOVAs) are used to compare the means between independent groups[280]. Clinical researchers must remember that statistical significance is limited only to assess whether or not a difference exists between the groups. A statistically significant result is not always a clinically significant finding, and vice-versa. Clinically, relevant often refers to small changes in outcomes that are considered important or worthwhile to a practitioner or a patient, and would result in a change in patient care[279,280]. Thus, clinical research often needs to utilize additional statistical and clinical approaches to interpret data.

Statistical Approaches

Correlation

Correlation is a statistical procedure used to evaluate whether a relationship exists between two variables[280,281]. A scatter diagram is often used for visual clarification of the relationship; with the data points for each variable plotted along the X and Y axis of a graph. With an appropriate number of data points the strength and shape of the relationship can be identified. In a perfect

positive relationship, the data points of one variable would increase proportional to the other variable creating a straight line with a positive slope. Conversely, if lower values of one variable are associated with higher values of the other variable a perfect negative relationship would be demonstrated. However, perfect relationships are very rare. The *correlation coefficient (CC)* provides an index to quantify the relationship between the two variables. CC values range from -1.00 (perfect negative relationship) to 0.00 (no relationship) to +1.00 (perfect positive relationship). The strength of the association is represented by the magnitude of the value (ie. the closer a value is to ± 1.00, the stronger the association) while the direction of the relationship is represented by a positive or negative sign of the correlation coefficient[280,281]. In general, values 0.00 to 0.25 represent little or no relationship; ±0.25 to ±0.50 suggest a fair relationship; ±0.50 to ±0.75 indicate a moderate to good relationship; and values above ±0.75 are considered an excellent relationship[280]. However, these cut-off points are simply a guide; sample size measurement error and the type of variables being studied should also be considered. For continuous, interval data the most commonly utilized measure of correlation is the Pearson product-moment coefficient of correction (***r***)[280]. The deviation of each score from the mean (moment) for the X and Y variable are considered. The product of the moments is a reflection of the degree of consistency within the distribution[280]. The study presented in chapter 2 utilized Pearson correlations to examine the relationship between the reach distances and composite score for the mSEBT and YBT. The study presented in chapter 3 utilized Pearson correlations to explore the relationship between anthropometric characteristics, knee proprioception, strength, ROM and flexibility with the reach distances of the YBT. The study in chapter 4 utilized Pearson correlations to evaluate the relationship between kinematic angles of the lower limb and YBT scoring.

Regression

While correlation statistics are able to describe the relationship between two variables, a linear regression analysis is necessary to determine if one variable is able to predict the outcome of the other variable[280]. In linear regression analysis the independent (predictor) variable is designated X, while the dependent (criterion) variable is Y. For data that is perfectly correlated, the data points would align in a straight line. However, as those cases are very rare a line of best fit (regression line) which gives the smallest sum of squares is used. The square of the CC (r^2), termed the *coefficient of determination*, represents the proportion of variance that the two variables have in common. The percentage of the total variance in the Y scores that can be explained by the X scores is represented by an r^2 value [280,281]. Thus, r^2 can provide a more meaningful description of the relationship between the variables, when X and Y are strongly correlated. Values for r^2 range between 0.00 and 1.00, with no negative sign as it is a squared value. The generalization of a regression analysis is limited by the range of scores used to derive the equation. The reference population for the analysis needs to be clearly defined, as prediction values will only be applicable to those within the specified population[280]. In addition to a correlation analysis, the study presented in chapter 3 used linear regression (r^2) to further explore the relationship between anthropometric characteristics, knee proprioception, strength, ROM and flexibility with the reach distances of the YBT.

Bland-Altman Assessment of Agreement

An assessment of the amount of agreement between the measures is needed when comparing a new measurement technique to an established one [281,282]. Correlation and regression analysis are considered appropriate techniques to measure the level of agreement between the variables. However, data which are in agreement can have a weak relationship[281,282]. A Bland-Altman plot

is an alternative approach, based on graphical representations and simple calculations, that can quantify the level of agreement between two quantitative measures[280–282]. The difference between the two paired measurements (***d***) is plotted against the mean of the two measurements (***X***) to give a visual analysis of their relationship. An upper and lower limit of agreement is set at two standard deviations above and below the Xd. In a normally distributed data set, it is expected that 95% of the difference scores fall within these limits (*95% limits of agreement*). The mean sum of all the differences is represented by the midpoint of the distribution (***Xd).*** The spread around the Xd helps researchers decide if the observed error is acceptable for one measurement method to be substituted by the other. If the measurements obtained from one method were exactly the same as the other measurement, *Xd* would be zero. A biased pattern would have Xd above (positive) or below (negative) zero indicating that the second method is consistently larger or smaller than the first (reference) method. In a biased pattern, the measurement methods may not be considered interchangeable however that decision is left to the discretion of the interpreter. The plot simply quantifies the bias and the range of agreement. How far apart the measurements can be without causing difficulties depends on the specific measurement methods and specific clinical criteria, and should be defined in advance. The study in chapter 2 utilized the Bland-Altman assessment of agreement to compare the performance in the three reach directions and composite scoring between the mSEBT and YBT methods.

Clinical Approaches

Number Needed to Treat

The *number needed to treat* (NNT) is a clinical statistic that provides information about effectiveness of an intervention in terms of patient numbers. It refers to the number of patients who need to be treated to achieve one beneficial outcome in a given period of time. The NNT is

the reciprocal of the *absolute risk reduction* (ARR). The ARR is the difference between the control event rate and the experimental event rate. NNT is a number between 1 and infinity. In an ideal situation the NNT would be 1.0, indicating that every patient will benefit from the intervention and no one improves in the control group. A larger NNT indicates a less effective intervention[279,280]. In the study presented in chapter 5, the NNT was calculated to determine the clinical effectiveness of the perturbation-based NM training program.

Chi-Square Statistic

Chi-square ($\mathbf{x^2}$) is a non-parametric statistic used to determine if an observed frequency differs from the frequency that would be expected by chance[283]. For this statistic, actual patient numbers are represented in mutually exclusive categories, such as patients who did and those who did not obtain clinically significant improvements in the YBT reach direction, as presented in chapter 5. The categorical data are arranged in a 2 x 2 *contingency table*, with independent variables in rows and the dependent variable in columns. The observed frequencies are entered in each cell, while the expected frequency is calculated for each cell in the table (accounting for the observed proportion for each variable). When the expected frequencies are less than 5, a procedure called the *Fisher Exact Test* is recommended. This provides the exact probability of the occurrence of the observed frequencies but the calculations are quite complex, thus most often generated by a statistical software program[280,283].

Chapter 2 - The Star Excursion Balance and Y-Balance Tests Differ when Assessing Physically Active Healthy Adolescent Females

1. Abstract

Background: The Star Excursion Balance Test (SEBT) and Y-Balance Test (YBT) are two common methods for clinical assessment of dynamic balance. Clinicians often use only one of these test methods and one outcome factor when screening for lower extremity injury risk. Dynamic balance scores are known to vary by age, sex and sport. The physically active adolescent female is at high risk for sustaining lower extremity injuries, specifically to the anterior cruciate ligament (ACL). Thus clarity in dynamic balance testing of adolescent females is important. To date, no studies have directly compared the various outcome factors between these two dynamic balance tests for this population. *Hypothesis:* Measured reach distances for three directions, a calculated composite score and side-to-side limb asymmetry for the ANT reach direction will differ between the mSEBT and YBT for physically active healthy adolescent females. *Study Design:* Cross-sectional study. *Methods:* Twenty-five healthy, physically active female adolescents (mean age, 14.0 ± 1.3 years) participated. Select reach distances, a composite score and side-to-side limb asymmetry for the SEBT and YBT, for each limb, were compared using Student T-tests, Pearson correlations and Bland-Altman assessments of agreement. *Results:* There were significant differences between the measured reach directions between the SEBT and the YBT. Injury risk classification, based on limb asymmetry in the anterior reach direction, differed between the tests. However, the calculated composite scores from the two tests did not differ. *Conclusions:* Although both tests can be used clinically to measure dynamic balance, performance scores on a particular reach direction should not be used interchangeably between the mSEBT and YBT in physically active adolescent females. *Clinical Relevance:* Investigations of adult and collegiate athletic populations have noted differences within and between the SEBT and YBT; however the literature lacks information regarding clinical dynamic

balance tests for healthy active adolescent females. Clinicians need to use specific test and population values for analysis, interpretation and injury risk classification of dynamic balance test results. Interpreting reach distance, calculated composite scores and side-to-side asymmetry measures for healthy active adolescent females should be cautious when comparing them to scores achieved for sport-specific adult populations.

Key Words: anterior cruciate ligament; dynamic balance; lower extremity; movement system; screening tool.

2. Introduction

Clinicians often use dynamic balance tests as a functional screen to identify athletes at-risk of injury, assess deficiencies following injury, and monitor rehabilitation progress[35]. The Star Excursion Balance Test (SEBT)[36,37] and Y-Balance Test (YBT)[38,39] are two reliable methods commonly used to clinically assess dynamic balance of the lower extremity. The time consuming 8-reach direction SEBT is often modified (mSEBT) to use only 3-reach directions: Anterior (ANT), Posteromedial (PM) and Posterolateral (PL)[256,258,259]. The commercially available YBT is an instrumented version of the mSEBT, designed to improve repeatability and standardize test procedures[38]. Both the SEBT and YBT simultaneously assess range of motion, flexibility, neuromuscular control and strength[40]. If clinicians can accurately identify healthy adolescent female athletes who may be at an increased risk for sustaining lower extremity injuries, they can then advise and implement intervention strategies to address the factors associated with the epidemic of lower extremity injuries (especially to the ACL) seen in this population. Within each test, there are a number of factors that can be reported and analyzed to assess lower extremity injury risk, such as the maximal reach distance measured in specific reach directions, a calculated composite score and side-to-side asymmetries in the anterior reach direction. Normative dynamic balance performance scores vary depending on the age, sex or specific sport played of the population[43–49]. Ankle injuries have been linked to a reduced reach distance in the PM direction in recreationally active college students[284], while ankle sprains in high school and college football athletes were linked to a reduced reach distance in the ANT direction[285]. Normalized composite scores of less than 94% on the mSEBT in high-school female basketball players[47] and less than 86.5% in college football players[43] on the YBT indicate a significant risk of lower extremity injury. The likelihood of sustaining a noncontact lower limb injury is also

increased with ANT reach distance asymmetry between limbs of greater than 4 cm in high school basketball players for the mSEBT[47] and division I athletes for the YBT[286].

Although the tests are very similar in nature, there are differences in the neuromuscular demands associated with each test. Within an healthy adult population reach distances and kinematic profiles differ between the mSEBT and YBT suggesting that the values between tests should not be used interchangeably[41,42]. With the variability in performance between subjects of different ages, sexes, and sport participation[46,287], it has been suggested that normative data, and injury risk thresholds or cut-off scores should only be utilized for comparison with the specific test and participant population from which they were developed[252].

Several investigations of adults and collegiate populations have noted differences within and between the SEBT and YBT[41,42], however the literature lacks information regarding clinical dynamic balance tests for healthy active adolescent females. Although the relationship between the two dynamic balance scores for the adolescent female population is currently not known, it is of particular interest as this demographic carries a high risk of sustaining lower extremity injuries, specifically to the anterior cruciate ligament (ACL) of the knee. Active adolescent females are 4-6 times more likely than males to sustain an ACL injury when participating in the same sports[29]. Additionally, young female athletes who return to sport following an ACL injury have the highest rate of re-injury (ipsilateral and contralateral) and are at 30-40 times greater risk of ACL injury compared to uninjured adolescents[288]. Clinicians may be incorrectly classifying young female athletes from inadvertently interchanging indices of performance between the SEBT and YBT, or using injury-risk thresholds that were established for a different population.

The purpose of the current study was to determine if there was an association between the mSEBT and YBT scores for measured reach distances, calculated composite score and side-to-side limb asymmetry in the ANT direction in physically active healthy adolescent females. As there are reported inconsistencies between the tests in an adult population, we hypothesized that all three factors would differ between the mSEBT and YBT for our population.

3. Methods

3.1 Participants

Following approval from the University's Health Research Ethics Board (H2014:302), 25 recreationally active adolescent females with no recent trauma to the lower extremity were recruited from the community to participate in this laboratory-based study. An a priori power analysis using data from a previous study of healthy recreationally active adults indicated that 22 subjects would be adequate to assess the mSEBT.[48,289] Inclusion criteria stated that volunteers were required to be female, 12-18 years of age, with no history of a lower limb musculoskeletal injury or concussions in the past 6 months. Participants were excluded if they failed a standardized screening criteria protocol by having knee joint effusion, being unable to fully flex and extend the knee joint, demonstrating quadriceps lag with an active straight-leg raise, having quadriceps strength less than 75% of the unaffected leg on manual muscle testing or being unable to perform 10 consecutive hops pain free[33]. Informed consent was obtained from parents and participants prior to initiation of study activities.

3.2 Testing Protocol

Demographic information, such as age, leg dominance (based on the leg preference for kicking a ball) and sport participation were collected. Maturation status was determined using the self-reported pubertal maturation observational scale (PMOS)[290]. The Physical Activity Questionnaire for Adolescents (PAQ-A) assessed physical activity level as a score of 1-5, 1 indicates a subject is minimally active and 5 extremely active[291]. Anthropometric data including height and weight were measured. The mSEBT and the YBT were completed according to previously described protocols[38,40], and required subjects to perform testing while barefoot, maintaining their hands on their hips. For the mSEBT, subjects performed a series of single-limb squats using the non-stance limb to touch a point a maximum distance along designated lines on the ground (Figure 2.1). While the SEBT can be used to evaluate 8 different reach directions; the modified version only involves recording the maximal reach distance for three directions: ANT, PM and PL. The mSEBT has been established as a reliable measure of dynamic balance in adolescents, with intra-rater intraclass correlation coefficients (ICCs) ranging from 0.82 to 0.87 and coefficients of variation ranging from 2.0% to 2.9%.[47] Pilot study results from our lab indicated inter rater ICCs ranged from 0.69 to 0.95 for the YBT reach directions and from 0.59 to 0.75 for the SEBT reach directions.

The YBT (Move2Perform, Evansville, IL) is a commercially available, instrumented product that is used to evaluate the same three reach directions as the mSEBT (Figure 2.2). Subjects maintain a one-legged stance on an elevated stance platform from which three pieces of plastic pipe extend in the specific ANT, PM and PL directions. With the non-stance foot, participants push an indicator to a maximum distance along the pipe, marked with 0.5 cm increments. A previous

study indicated that the YBT is a reliable method for assessing dynamic balance; within session inter-rater ICCs 0.54 to 0.82 and typical error values of 5.9% in children[48].

For both tests, subjects performed the recommended four practice trials, in each direction prior to completing the three test trials on each limb[38,256]. A standardized order of testing was utilized, the right stance limb was measured first in the order of ANT, PM and PL. Testing was repeated in the same order for the left stance limb. If the subject removed their hands from their hips, lost their balance or rested their reaching foot on the ground (mSEBT), kicked the reach-indicator plate to gain more distance (YBT), made contact with the ground on the reach or return to bilateral stance to gain balance, or lifted or shifted any part of the stance foot the trial was considered incomplete, and was repeated. The distance of the toe touch reached along each direction was marked and subsequently measured by an investigator for the mSEBT, while the most proximal edge of the reach indicator from the apex of the YBT was recorded.

The average of three successful test trails for each reach direction was used for data analysis. Limb length (LL) was measured from the anterior superior iliac spine to the most distal aspect of the ipsilateral medial malleolus in supine lying[36]. All reach distances were normalized as a percentage of the stance limb length using the formula [% = (excursion distance/LL) x 100]. A composite score, which is an average of all three reach distances, [Comp= ((ANT+PM+PL)/(3 x LL)) x 100] was also calculated for each limb. The absolute difference in the anterior reach direction distance (centimeters) between limbs was calculated to assess side-to-side asymmetry[252].

3.3 Statistical Analysis

Descriptive data for both the mSEBT and YBT were calculated. Student paired t-tests were used to test the differences in reach distance scores between limbs and between the mSEBT and YBT. For the measured reach distance scores of the SEBT differences of at least 6-8% are needed to feel confident that a clinical change in performance has occurred[289]. A Bonferroni correction alpha level of $P < 0.004$ (0.05/12) was used to compare the right and left limb because of the standardized test order of mSEBT followed by YBT, with the right limb reach directions always tested prior to the left limb. An alpha level of $P < 0.05$ was set for all other comparisons[41]. Effect sizes (Cohen's d) for the differences between the SEBT and YBT scores were calculated with values less than 0.2, 0.21 to 0.79, and above 0.80 considered to represent weak, moderate and strong[292]. Pearson correlations and Bland-Altman assessments of agreement were used to compare performance on all three reach directions and the composite score for the mSEBT and YBT[41,42,282]. Correlation coefficients *(r)* of 0.25-0.49, 0.50-0.74, and 0.75-1.0 were considered to represent weak, moderate and excellent relationships[280]. The absolute difference in the anterior reach distance (centimeters) between limbs was assessed with Student paired t-tests, and compared with the established absolute side-to-side asymmetry injury risk cut-off value of greater than 4cm[47,286].

4. Results

Demographic information and anthropometric data for participants are presented in Table 2.1. Results indicate that participants were predominantly post-pubertal adolescents with a normal BMI, right leg dominant and participated in a variety of sport activities. Separate 1-way analysis of variance based on maturation status and activity level found these factors had no significant impact on dynamic balance reach direction scores, thus all subjects were grouped together for

comparison of the tests. Comparison between the right and left limb indicated that there were no statistically or clinically significant differences for either the mSEBT or the YBT. Statistically and clinically significant differences were observed between the mSEBT and YBT for all three measured reach directions. However, no significant differences were noted between the two procedures for the calculated composite scores or absolute asymmetry in the anterior direction (Table 2.2). Effect size calculations indicated that results were moderate to strong for all three measured reach distances, but weak for the composite score and absolute asymmetry. Pearson product-moment correlation coefficients between the mSEBT and YBT indicated a moderate to excellent relationship for all the measured reach directions, except the left limb in the anterior direction and the right limb in the posterolateral direction which both had a weak relationship (Table 2.3). Bland-Altman assessments of agreement between the mSEBT and YBT indicated that there was a bias between the three reach directions, however the calculated composite scores showed good agreement (Table 2.4). Two subjects had a greater than 4 cm absolute asymmetry in the anterior direction for the mSEBT and a different two subjects for the YBT (Figure 2.3).

5. Discussion

To our knowledge, this is the first report to compare the results from the mSEBT and YBT with a healthy physically active female adolescent population that is at significant risk for lower extremity injury. The main finding of this investigation was that measured participant scores for the three reach directions differ between the mSEBT and YBT. The anterior reach distance was greater for the mSEBT than the YBT, interestingly the posteromedial and posterolateral distances were less for the mSEBT than the YBT. In contrast, the opposing skewness of the measured reach directions resulted in similar values for the calculated composite scores for the tests. Also the established injury risk cut-off score of greater than 4 cm absolute asymmetry in

the anterior direction identified different subjects at-risk of injury depending on the test method. As a consequence, caution should be used when comparing the results from the mSEBT and the YBT for a healthy physically active adolescent female population. When comparing scores to the reported values for other populations within the literature, the test scores should remain exclusive to their specific population and test method[41,42,252].

Demographic data confirmed that participants were young, physically active individuals engaged in a wide range of sporting activities. This is important as it serves to extend the findings of other investigations on the YBT and mSEBT which focused on sport specific populations (such as basketball or soccer)[47,49], age specific populations (i.e., college-aged or young adults)[45,258,289], or specific competitive levels within sport (i.e., Division I or elite athletes)[44,286]. Our data are representative of a typical adolescent female population that participates in a variety of sporting activities and is nearing or has recently reached physical maturation. Anthropometric data also help to confirm that our adolescent females were representative of a healthy population that included individuals with various body types (tall/short; thin/muscular, etc.)[293]. Again, this finding serves to enhance the overall generalizability of our results to a general population of recreationally active adolescent females. Clinical measures of dynamic balance are a critical component of pre-participation screening in this population[35].

Two previous studies compared performance on the SEBT versus YBT for healthy active male and female adult populations. For reach in the anterior direction, both studies found a difference between the SEBT and YBT[41,42]. One suggested that disparities in posture control strategies may be responsible for the differences between the tests, and hypothesized that the SEBT

predominately relies on a feed-forward control strategy until contact is made with the toe touch[41]. By comparison the same report suggested that during the YBT, constant proprioceptive feedback is received as the reach-foot toe remains in contact with the reach-indicator throughout the excursion (feedback control)[41]. Additionally, while the stance platform is relatively low, the slight elevation in stance position maintained during the YBT may also contribute to the decreased reach distance[41]. The other study[42] speculated that the performance of the SEBT and YBT differed in relation to dynamic neuromuscular demands, as evident by the difference the anterior reach distances and associated kinematic profiles. For anterior reach, there was a negative correlation between reach distance and hip-joint sagittal-plane angular displacement for the SEBT (i.e., as hip joint flexion increased, reach distance decreased). In contrast, there was a positive relationship between reach distance and hip-joint sagittal plane angular displacement during performance of the YBT (i.e., as hip joint flexion decreased, reach distance decreased)[42].

In addition to anterior direction differences, our results indicate that the reach distances for the posteromedial and posterolateral directions also differed between the mSEBT and the YBT. This is not consistent with the findings of the two reports noted above[41,42]. The sensorimotor system that regulates balance and postural awareness relies on information from the visual, vestibular and somatosensory subsystems[294]. When reaching in the anterior direction subjects receive visual feedback on their performance. However, in the posteromedial and posterolateral directions visual awareness is lower, which places a greater reliance on the non-visual somatosensory system. Coughlan et al.[41] reported that the reach distance achieved in the anterior direction was less for the YBT compared to the SEBT. When visual awareness was decreased in the posterior directions, a similar score was achieved between the SEBT and YBT. Their report suggested this

increase in YBT performance relative to SEBT was due to the increased somatosensory feedback for the YBT due to the constant toe contact with the reach-indicator[41]. An important difference between the previous studies and the present investigation is the demographic characteristics of participants. Subjects in that study were healthy adult males 22.5±3.05 years of age while we assessed healthy adolescent females. Pubertal growth is reported to inhibit the sensorimotor functions of the lower extremity; thus, during dynamic postural control tasks adolescents heavily rely on visual cues[154]. The impaired non-visual somatosensory systems in adolescents may be the reason why the same increase in YBT performance relative to the SEBT is not demonstrated in our population. This may explain why performance in the posterior reach directions of the mSEBT and YBT were different for our subjects, yet were the same in an adult population[41]. Protocol variations in which our testing occurred during one session while these other two studies[41,42] conducted each dynamic balance test a week apart may have also contributed to the differences observed in the posterior reach directions. The present results indicate that female adolescent subjects performed differently on both the SEBT and YBT assessment methods when compared to an adult population. Caution should be used when interpreting and comparing reach distance performance for adolescents to those achieved by adults.

In addition to the measured reach directions, a composite score was calculated for both the mSEBT and YBT. Bland-Altman analysis of the data indicated that for the anterior reach direction, the mSEBT distance was greater than YBT. However, the mSEBT reach distances were less than the YBT for both the posteromedial and posterolateral reach directions. Thus, when the composite score was calculated, the positively and negatively skewed reach values resulted in a value which was similar between the two tests. The inherent scoring differences in

different reach directions, and possible differences in overall dynamic balance, are concealed when the assessment only includes the composite score values. Therefore, we recommend that when assessing dynamic balance, participant performance on the individual reach directions should be analyzed, in conjunction with the calculated composite scores, as our results indicates that examination of only the composite score may not accurately reflect the true differences in dynamic balance performance for each test. Composite score values alone are often used in the literature to assess sport-specific risk of injury. A normalized SEBT composite score of less than 94.0% was shown to indicate the risk of a lower extremity injury in high school basketball players[47]. College football players who score less than 89.4% on the normalized YBT composite score are also at an increased risk of injury[43]. The average composite scores for our subjects were above both of these cut-off values for both the mSEBT and the YBT. Based on the above reported values for injury risk, our mSEBT results indicated that five of our subjects were vulnerable to a lower extremity injury. For the YBT, only four subjects were at an increased risk of injury. Furthermore, only one individual was identified as susceptible to injury via both test cut-off values. The remaining at-risk individuals identified in the mSEBT were different from those identified in the YBT, once again highlighting that a difference between the tests exists. This suggests that the sport-specific injury risk dynamic balance composite score cut-off values for high school basketball and college football players may not be accurate for physically active adolescent females[46]. Determination of such injury risk cut-off values for physically active adolescent females was beyond the scope of this study, and would be very useful for future application.

Asymmetries between limbs is also often used as a screening tool to determine those who may be at increased risk of sustaining an injury[43,47]. A difference in the raw anterior reach distance of more than 4cm between limbs for either the mSEBT[47] or the YBT[286] is clinically significant, and suggests a greater likelihood of sustaining a noncontact lower limb injury[39,47,48,258,289]. Recently, Stifler et al.[252] found that in Division I collegiate athletes' side-to-side asymmetry in the anterior reach direction of the SEBT was associated with injury. As dynamic balance scores vary based on age, sex and sport[46] it is unknown if this established injury risk cut-off value is appropriate for female adolescent athletes. To our knowledge, we are the first to compare injury risk classification based on limb asymmetry between the mSEBT and YBT for the recreationally active female athlete. Analysis of our raw anterior scores indicated that two subjects using the mSEBT and a different two subjects using the YBT had asymmetries of more than 4cm. Once again our results indicate that there is a difference between the two test methods for our specific population. Further investigations of this population with a larger sample size are required to assess healthy and injured subjects to determine an appropriate cut-off value for each of the test methods.

Typically, clinicians will only complete one dynamic balance test as part of an evaluation. Both the mSEBT[47] and YBT[48] are reliable; as such, either test would be appropriate to assess dynamic balance in adolescent females. Each test protocol has its own strengths and limitations. The SEBT does not require costly equipment and allows an evaluator to assess 5 reach directions in addition to the 3 used for the modified protocol. However the toe touch is harder to quantify and control in the SEBT. The instrumented YBT may provide quicker and more standardized measurements, it is limited to assessing only the anterior, posteromedial and posterolateral reach

directions and may not be financially feasible for all clinicians. The goal of the present study was not to assess whether one test is superior to the other in assessing dynamic balance. The purpose was to evaluate whether the outcome factors of reach distance, composite scores and side-to-side limb asymmetry in the ANT direction of the mSEBT are interchangeable with those of the YBT, and to determine if previously reported thresholds determined in other populations would be accurate when classifying adolescent female athletes at-risk of injury. Although most test scores were found to have a moderate positive correlation between the two test methods based on Pearson product-moment correlations, t-test results showed that the absolute values of the mSEBT reach directions are not interchangeable with the absolute reach values of the YBT. This means that if a subject had a high reach distance on the mSEBT, they would also have a high score when performing the same reach direction on the YBT. But a reach distance score of 94% on the mSEBT, was not the same as a reach distance of 94% on the YBT. Subjects are inconsistently classified as at-risk for an injury when using the previously established cut-off value of greater than 4 cm asymmetry in the anterior reach direction. Researchers and clinicians should be aware of these inherent differences when interpreting and implementing these dynamic balance tests.

It is important to acknowledge that our study did have several limitations, primarily related to the specific population which limits the external validity, but addresses an important deficiency in the literature regarding clinical dynamic balance tests for this population. While several sport-specific reports examined the SEBT and YBT in female athletes, the diverse group of sporting activities of our subjects allows us to provide commentary on a more broad-based population of athletes. This population is of particular interest to clinicians as athletically active adolescent

females are at a high-risk of sustaining lower extremity injuries. Our a priori power analysis indicated that our sample size was appropriate to assess the dynamic balance tests[48,289]. Effect size calculations confirmed that sample size for the measured reach directions of the SEBT and YBT were adequate, however sample size was a limitation for the composite score and absolute side-to-side limb asymmetry. While future studies will need a larger sample size to establish normative values for both healthy and injured physically active adolescent females, this investigation is the first to report dynamic balance scores for a recreationally active adolescent female population, drawn from a diverse sporting population. Importantly, placement of the stance limb foot varies between the mSEBT and YBT: in the mSEBT, the heel is aligned to the centre of the mSEBT grid[35], and for the YBT, the toes of the stance limb are aligned to the centre of the grid. Differences in the anterior reach distances between the tests may be directly related to this variation. In future studies comparing the test procedures, the mSEBT should adapt the standardized foot position of the YBT.

6. Conclusion

Results found differences in the measured reach distance performance on the mSEBT and YBT, and that at-risk injury cut-off values for side-to-side asymmetry in the anterior reach direction need to be established for the healthy physically active adolescent female population. Although both tests can be used clinically to measure dynamic balance, performance scores on a particular reach direction should not be used interchangeably between the mSEBT and YBT in this population. Since administration of the SEBT and YBT protocols varies within the literature, specific detailed methodology should be carefully reviewed by clinicians and researchers when interpreting dynamic balance scores and using cut-off values to classify individuals at-risk of injury. Further research is clearly needed in order to establish normative values for the SEBT and

YBT in the adolescent female population, and determine the limits of reliability for dynamic balance testing in healthy and ACL-injured individuals.

7. Chapter 2 Tables and Figures

Table 2.1: Participant demographic and anthropometric information.[mean ± SD, (95% confidence interval)]

	Adolescent Females (N=25)
Age, y	14.0 ± 1.3 (13.5, 14.5)
Height, cm	163.1 ± 5.8 (160.7, 165.5)
Weight, kg	59.7 ± 15.5 (53.3, 66.0)
BMI, kg/m^2	22.3 ± 4.8 (20.3, 24.3)
Maturation status, n	
Pre-pubertal	3
Mid-pubertal	5
Post-pubertal	17
PAQ-A scale	2.9 ± 0.8 (2.6, 3.2)
Leg dominance, n	
Right	22
Left	3
Sports, n	
Basketball	1
Badminton	1
Baton	4
Dance	4
Cross country running	1
Gymnastics	2
Hockey/Ringette	5
Soccer	2
Softball	1
Tennis	1
Volleyball	3

Abbreviations: BMI, body mass index; PAQ-A, physical activity questionnaire for adolescents

Table 2.2: Measured reach distances, calculated composite scores and absolute side-to-side asymmetry for the mSEBT and YBT. [mean ± SD, (95% confidence interval)]

	mSEBT	YBT	P Value	Effect Size†
Anterior direction, % limb length				
Right limb	94.9 ± 6.4 (92.2, 97.5)	65.6 ± 5.1 (63.5, 67.7)	< 0.01*	5.1
Left limb	96.1 ± 5.1 (94.0, 98.2)	57.0 ± 4.5 (55.1, 58.9)	< 0.01*	8.1
Posteromedial direction, % limb length				
Right limb	90.1 ± 10.8 (85.6, 94.6)	100.3 ± 7.0 (97.4, 103.2)	< 0.01*	1.1
Left limb	90.7 ± 9.2 (86.9, 94.5)	101.0 ± 6.9 (98.1, 103.8)	< 0.01*	1.3
Posterolateral direction, % limb length				
Right limb	83.2 ± 11.9 (78.3, 88.1)	98.5 ±7.8 (95.3, 101.7)	< 0.01*	1.5
Left limb	83.8 ± 11.9 (78.8, 88.7)	101.0 ± 7.9 (97.7, 104.3)	< 0.01*	1.7
Composite score, % limb length				
Right limb	103.5 ± 10.9 (99.0, 108.0)	102.1 ± 8.7 (98.5, 105.7)	0.62	0.1
Left limb	104.6 ± 10.7 (100.2, 109.0)	103.6 ± 8.8 (100.0, 107.2)	0.44	0.1
Absolute asymmetry, cm				
Anterior direction	2.1 ± 1.8 (1.4, 2.8)	2.0 ± 1.3 (1.5, 2.5)	0.68	0.1

Abbreviations: mSEBT, modified star excursion balance test; YBT, y-balance test

* $P < 0.05$

†Cohen's d

Table 2.3: Correlation (*r*) between reach distances for the mSEBT and the YBT.

	Pearson product-moment correlation coefficient (*r*)	P Value
Anterior direction, % limb length		
Right limb	0.51	0.01*
Left limb	0.48	0.01*
Posteromedial direction, % limb length		
Right limb	0.54	0.005*
Left limb	0.66	<0.01*
Posterolateral direction, % limb length		
Right limb	0.41	0.04*
Left limb	0.65	<0.01*
Composite score, % limb length		
Right limb	0.61	0.01*
Left limb	0.79	<0.01*

Abbreviations: mSEBT, modified star excursion balance test; YBT, y-balance test
* $P < 0.05$

Table 2.4: Bland-altman assessments for agreement between the mSEBT and the YBT.

	d	SD_{diff}	95% limits of agreement
Anterior direction, % limb length			
Right limb	29.3	5.8	17.8, 40.7
Left limb	30.2	4.7	20.9, 39.4
Posteromedial direction, % limb length			
Right limb	-10.2	9.1	-28.8, 7.7
Left limb	-10.4	7.0	-24.1, 3.3
Posterolateral direction, % limb length			
Right limb	-15.3	11.2	-37.3, 6.7
Left limb	-17.2	9.0	-34.9, 13.8
Composite score, % limb length			
Right limb	1.4	8.9	-16.0, 18.7
Left limb	1.0	6.6	-11.9, 13.9

Abbreviations: d, mean difference; SD_{diff}, standard deviation of the differences.

Figure 2.1: Modified star excursion balance test (mSEBT) for the left stance limb. a: Anterior reach direction; b: Posteromedial reach direction; c:Posterolateral reach direction.

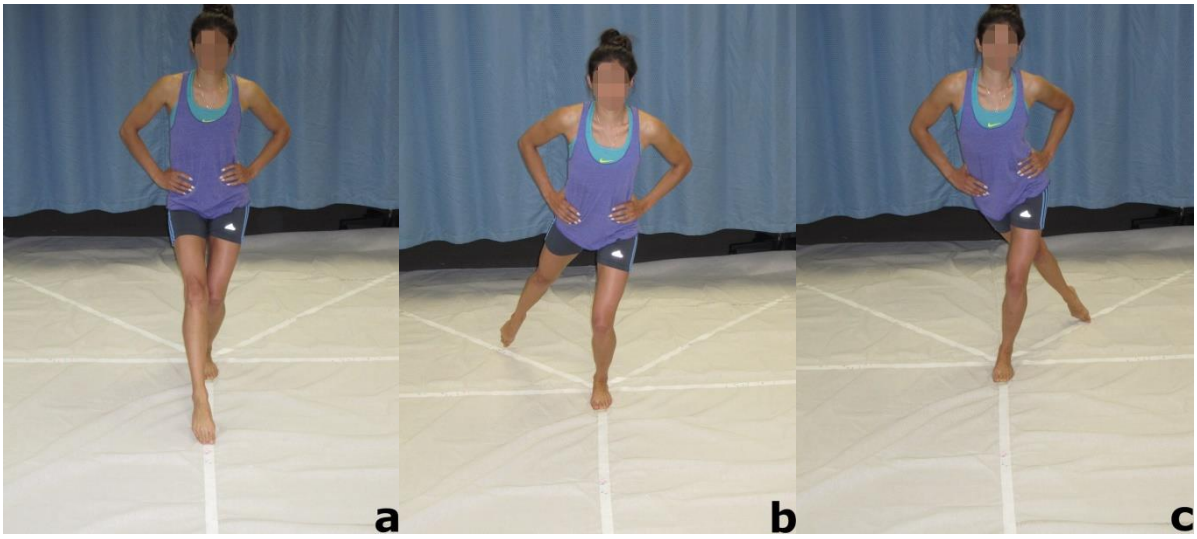


Figure 2.2: Y- balance test (YBT) for the left stance limb. a: Anterior reach direction; b: Posteromedial reach direction; c:Posterolateral reach direction.

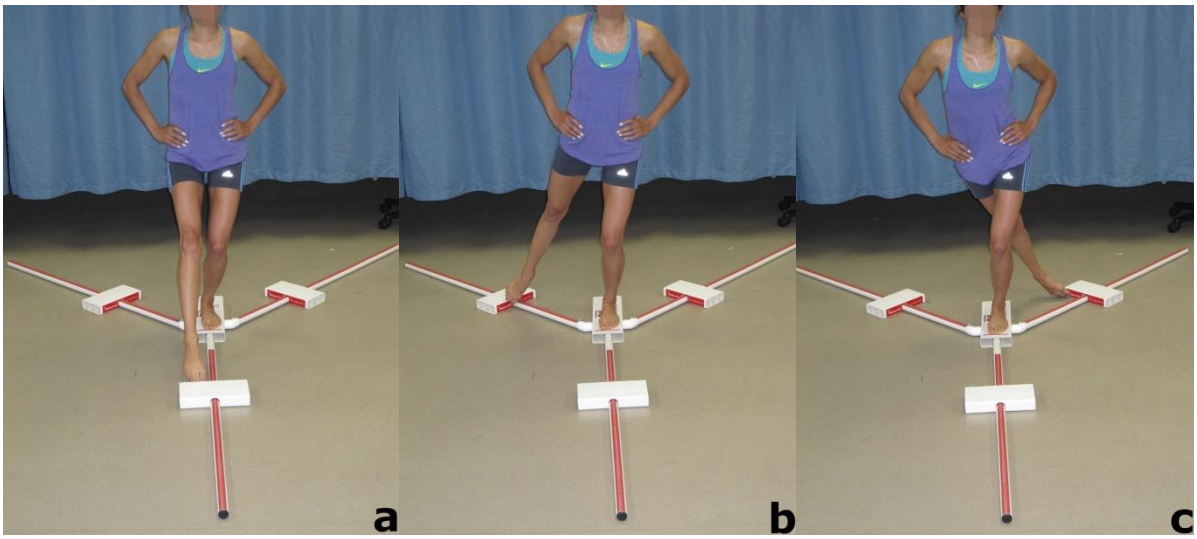
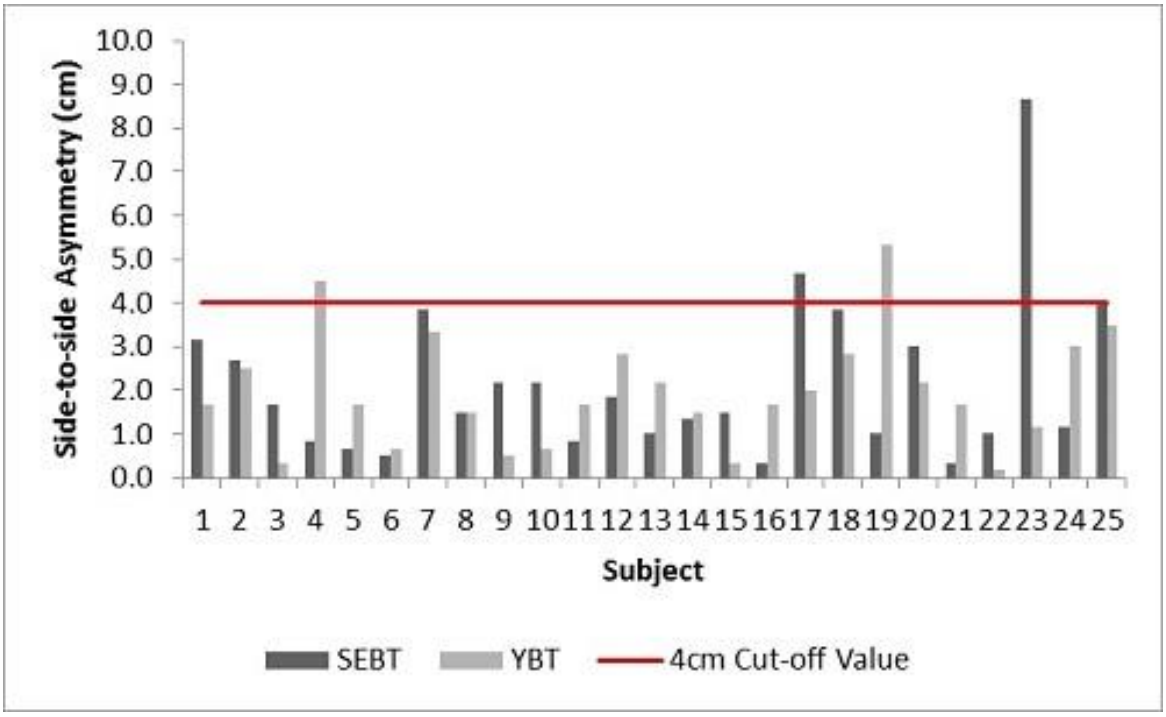


Figure 2.3: Absolute side-to-side difference in the anterior reach direction.



Chapter 3 - The Relationship between Anthropometric Characteristics, Lower Limb Strength and the Y-Balance Tests for Healthy and ACL-Injured Adolescent Females

1. Abstract

Background: Adolescent females are an at-risk population to sustain injuries to the anterior cruciate ligament (ACL). The Y-Balance Test (YBT) is a common clinical tool to screen athletes at risk of injury, assess deficiencies after injury, and monitor progress in rehabilitation. The relationship between anthropometric and lower extremity variables with the YBT has yet to be investigated for this population. *Objectives:* To determine whether performance on the YBT in adolescent females is influenced by anthropometric and lower extremity variables of proprioception, range of motion (ROM), flexibility, and strength. *Study Design:* Prospective cohort. *Methods:* 25 healthy and an exploratory group of 10 ACL-injured adolescent females were included. T-tests were used to test for differences for all variables between the dominant healthy and ACL-injured limbs. Simple linear regression was used to explore the relationship between anthropometric characteristics, knee proprioception, strength, ROM and flexibility with each of the YBT reach directions. *Results:* Healthy and ACL-injured subjects demonstrated similar YBT reach distances. In healthy subjects, weight and BMI had moderate inverse correlations with the posterior reach directions of the YBT. Lower extremity strength was positively correlated with the PM and PL reach directions. In contrast, the exploratory group of ACL-injured subjects showed no relationships between the anthropometric characteristics, lower extremity strength and the YBT. *Conclusions:* Anthropometric measures and strength of the lower extremity correlated with the YBT in healthy adolescent females. Although YBT reach distance was similar for healthy and ACL-injured subjects, the two groups demonstrated different relationships of YBT and selected anthropometric and lower extremity variables. Further investigations are needed to address the underlying mechanisms that contribute to dynamic postural stability.

Key Words: anterior cruciate ligament, dynamic balance

2. Introduction

Dynamic postural stability is the ability to use segmental and whole-body movement to maintain balance when the center of mass is moved beyond the base of support[40]. Assessment of dynamic postural stability reflects similar maneuvers in athletic activity. In addition to sensory proprioception, dynamic postural stability requires integration of the vestibular and visual systems[295,296]. Proprioception develops very early, while vestibular and visual systems are still maturing during adolescence[297]. Interestingly, sex differences in balance control[297] and the risk of anterior cruciate ligament (ACL) injuries[29] appear simultaneously during this period of development. In general, while adolescents involved in sports are the population most at-risk to sustain a lower limb injury[298], active adolescent females are 4-6 times more likely than males to sustain an ACL injury when participating in the same sports.[29] Additionally, young female athletes who return to sport following an ACL injury have the highest rate of secondary ACL injury (ipsilateral and contralateral) at 23%[288]. Decreased balance, proprioception, strength and neuromuscular control are known risk factors for lower extremity injury in females[13,38,49,76,159]. Such deficiencies often lead to a dynamic valgus position at the knee (adduction and internal rotation) during sports participation, which increases stress on the knee joint and load on the ACL[13,159].

Anthropometric characteristics[299–301], range of motion (ROM)[41,42,268,302], flexibility[303] and strength[267,296,304–309] are all reported to contribute to dynamic balance. Currently there is no "gold standard" for measuring balance, as laboratory-based and clinical methods of measuring dynamic postural stability assess different components of balance[310]. Since measures of clinical performance are influenced by many factors including age, sex, body-mass index (BMI), injury and participation in specific sports, an assessment on a well-defined population is required[43–49].

Since we currently do not understand the relationships between anthropometric features, lower limb characteristics, and performance on clinical tests of dynamic balance such as the Y-balance test (YBT), the reliability of their use in assessing an at-risk adolescent female population is not certain.

In a laboratory setting, postural stability is typically assessed using center-of-foot pressure and moments measured from force plates or testing on a Biodex Balance System[299,300,311,312]. Higher body weight is considered to contribute to impaired dynamic postural control in adults[299,301,313] and adolescents[300,311,314]. Obesity also negatively impacts balance by altering the fitness-related variable of lower limb strength[311]. In addition to its effect on balance, weight has an impact on the risk of injury for young athletes: overweight and highly active youth have a higher risk of injury than healthy-weight youth[298].

In a typical clinical setting without ready access to specialized equipment, dynamic postural stability is commonly assessed using either the YBT[38,39] or the star excursion balance test (SEBT)[40]. Although the tests are similar in nature, the neuromuscular demands associated with performing each test are different[38]. For an adult population, reach distances and kinematic profiles differ between the YBT and SEBT, meaning that values for the two tests are not interchangeable[41,42]. The YBT was developed to standardize performance and score the three most frequently assessed reach directions of the SEBT: Anterior (ANT), Posteromedial (PM) and Posterolateral (PL)[38,256,258,259]. Clinical tests of dynamic balance are functional screens to identify athletes at risk of injury, assess deficiencies after injury, and monitor progress in rehabilitation[35]. They reflect lower limb range of motion or flexibility, neuromuscular control, and strength[40,315].

Most reports on the individual components of performance on YBT testing have included both male and female adult participants[40,302,303,306–309,316,317]. Ankle dorsiflexion range of motion is correlated to the ANT reach distance[303] and kinematic profiles during the YBT indicate that motions at the trunk, hip, knee and ankle can predict performance[302]. A strong relationship between hip and knee strength and YBT reach is especially noted in adult females[306–309].

Poor performance on clinical tests of dynamic postural stability predicts higher risk of lower limb injury, such as ankle sprain and ACL injury[43,47,285,286]. Furthermore, individuals with an ACL-deficient limb show deficits in dynamic postural control in that limb compared to the uninvolved limb[267,296] and relative to healthy asymptomatic controls[318]. The purpose of this investigation was to fill the gap in information in clinical dynamic balance testing in an at-risk population. The primary hypothesis was that there would be differences in the YBT reach distances in healthy and ACL-injured. Additionally, it was hypothesized that YBT performance would be associated with anthropometric characteristics and lower extremity variables of proprioception, range of motion (ROM), flexibility, and strength in healthy and ACL-injured adolescent females.

3. Methods

3.1 Participants

Following institutional ethics approval (H2014:302), adolescent females were recruited from the community to participate in this clinical study. A power analysis ($n=2\{(1.96+0.84)9.5/8\}^2$) from a previous study of healthy, recreationally active adults indicated that 22 subjects was required to reliably assess dynamic balance[48,289]. The study included 25 healthy adolescents and an exploratory group of 10 ACL-injured subjects. Informed consent was obtained from parents and

participants prior to starting study activities. Adolescent females who were recreationally active in a variety of sports participated in the study. Healthy subjects reported no recent trauma to the lower extremity. Inclusion criteria stated that volunteers were required to be female, 12-18 years of age, with no history of any other lower limb injury or a concussion in the past 6 months. The ACL-injured group were evaluated clinically by an orthopaedic surgeon, and had diagnosis confirmed by magnetic resonance imaging. However, the presence of secondary joint lesions, such as meniscal injury and ligament tears were not obtained.

3.2 Testing Protocol

Demographic and anthropometric information, such as age, height, and weight were recorded, and BMI and the time since injury were calculated. Maturation status was determined using the self-reported Pubertal Maturation Observational Scale (PMOS)[290]. Leg preference for kicking a ball was used to determine leg dominance; a KT-1000 (MEDmetric Corp., San Diego, CA) was used to evaluate ACL laxity[319]. The International Knee Documentation Committee form modified for a pediatric population (Pedi-IKDC)[320] was administered to asses knee-specific symptoms and function. The level of overall activity was assessed via the Physical Activity Questionnaire for adolescents (PAQ-A)[321] and the main type of sport participation was were also collected.

Y-Balance Test

The YBT was completed according to previously described protocols[38]; subjects were barefoot with their hands on their hips (Figure 3.1). Subjects maintained a one-legged stance on an elevated platform from which 3 pieces of plastic pipe (marked in 0.5 cm increments) extend in the ANT, PM and PL reach directions. With the non-stance foot, participants pushed an indicator outward to a maximum distance along the pipe. The YBT is valid and reliable tool for assessing

dynamic balance in children, demonstrating within-session reliability values of between 0.54-0.82 and typical error values of 5.9%[48]. In the current protocol, subjects performed 4 practice trials in each direction before completing the 3 test trials. Tests were conducted with a standardized order: the right-stance limb was measured first in the order of ANT, PM and PL, then testing was repeated in the same order for left limb stance. Testing on ACL-injured subjects first assessed stance on the uninvolved limb, followed by ACL-injured limb stance. If a subject removed her hands from her hips, kicked the reach-indicator plate to gain more distance, made contact with the ground on the reach or return to bilateral stance to regain balance, or lifted/shifted any part of the stance foot, the trial was considered incomplete, and was repeated. The distance from the YBT apex of the most proximal edge of the reach indicator was recorded. The average of 3 successful trails for each reach direction was used for analysis. All reach distances were normalized as a percentage of each participant's stance-limb length (%LL), measured from the anterior superior iliac spine to the most distal aspect of the ipsilateral medial malleolus in a supine, lying position[36]. Subsequent use of the terms ANT, PM and PL will refer to the normalized reach distance achieved in the respective YBT direction.

Proprioception

Joint-position sense (JPS), the awareness of position in three dimensions, is a common test of proprioception, and incorporation of weight bearing (WB) tests provides a functional evaluation[322] with greater clinical relevance[323] for conditions such as ACL-injury where instability is experienced in WB[324]. Following published procedures[322,323], WB-JPS was assessed by asking subjects to maintain a unilateral stance, with the untested limb lifted off the ground, and minimal bilateral hand support. With eyes closed, the subject was instructed to slowly flex the knee of the WB limb and to stop at approximately 30 degrees of flexion, the test angle (TA). An electro-goniometer (Acumar Dual Inclinometer ACU0002, Lafayette Instrument Company,

Lafayette, IN) placed at the thigh and lower leg was used to evaluate knee-joint position. The TA was held for approximately 5 seconds before returning to an erect bilateral stance. The subject was then asked to reproduce the same amount of unilateral knee flexion, which is known as the response angle (RA). Absolute angular error (AAE) is a sign-less arithmetic difference between the TA and RA. The test was repeated 3 times, and the average for each limb was used for evaluation.

Range of Motion and Flexibility

ROM and flexibility of the lower extremity joints were measured using goniometric measurements and joint-specific tests, according to established protocols[303,325,326]. Subjects lay prone with the goniometer axis aligned to the knee joint. Subjects were asked to maximally bend their knee (flex), then straighten the leg by pressing the back of the knee toward the table (extend). The average of 3 measurements was used to represent knee ROM. A standing toe-touch test was used to assess hip-joint ROM[325]. Subjects stood on a step-stool with their feet hip-width apart and were instructed to keep their knees, arms and fingers straight while they bent forward as far as possible. The maximum reach position held for about 6 seconds was measured to the nearest 0.5 cm; the average of 3 trails was used for analysis[325]. Ankle-joint flexibility was determined using the weight-bearing lunge test (WBLT)[303]. Subjects were instructed to keep their test heel on the floor while flexing their knee towards the wall in front of them, and asked to maximize the distance from the great toe to the wall (measured in cm) while maintaining heel and knee contact. After practising 3 times, subjects had measurements collected for 3 test trails, the average of which was used for analysis[303].

Strength

Hand-held dynamometry (HHD) is a valid, reliable measure of isometric muscle strength in adolescents[327] and an ideal test method for use in the clinical setting[327,328]. The “make-test”

method was used, as it is preferred for use with adolescents: the examiner held the dynamometry instrument (Chatillon DFX II Series, Largo, FL) stationary while the subject gradually built resistance for a 5-second push against the dynamometer[327]. Standardized positions were used to assess knee flexion, knee extension, hip external rotation, hip abduction, and ankle plantar flexion[329]. Three HHD measurements for each movement were averaged. Strength scores for each subject were expressed as HHD force (N) relative to body weight (kg).

3.3 Statistical Analysis

Both limbs of each subject were tested, and preliminary analysis comparing the limbs was performed using T-tests. The dominant limb was used to represent healthy subjects, as there was only a significant difference between the right and left limb for one reach distance (PL). There were no differences between the limbs of the ACL-injured group. The affected limb was used to represent the ACL-injured subjects, following recommendations of previous reports[267]. Differences between the dominant limb of healthy subjects and the ACL-injured limb of the ACL-injured group were tested ($p<0.05$) using T-tests. Simple linear regression was used to examine the correlation coefficients (r) and the proportion of variance explained (r^2) in exploring the arithmetic relationships of anthropometric characteristics, knee proprioception, strength, ROM, and flexibility with reach distance in each of the three reach directions of the YBT[41,42,282]. Correlation coefficients *(r)* of 0.25-0.49, 0.50-0.74, and 0.75-1.0 were considered to represent weak, moderate and strong relationships[280].

4. Results

Demographic information and anthropometric data for participants are presented in Table 3.1. Participants were predominantly post-pubertal adolescents who were right-leg dominant and participated in a variety of sport activities. Although the ACL-injured group was slightly older

than the healthy group, anthropometric measurements were similar between groups, with the exception of measures for ACL laxity and the pedi-IKDC due to ACL-injury.

For each reach direction of the YBT, reach distance did not differ between healthy and ACL-injured subjects (Table 3.2).

Results of tests on lower extremity proprioception, ROM, flexibility, and strength are presented in Table 3.3. Healthy subjects had greater ROM for knee flexion ($P<0.001$) and greater strength in hip abduction ($P=0.01$) than ACL-injured subjects.

No significant correlations were found between the anthropometric and demographic features for the ANT ($P > 0.05$). In the PM, weight ($r = -0.53$, $r^2 = -0.29$, $P < 0.05$) and BMI ($r = -0.53$, $r^2 = 0.28$, $P < 0.05$) showed significant moderate negative correlation for healthy participants ($P < 0.05$) (Figure 3.2A). Similarly for the PL, weight ($r = -0.56$, $r^2 = 0.31$, $P < 0.05$) and BMI ($r = -0.51$, $r^2 = -0.26$, $P < 0.05$) also showed a significant moderate negative correlation for healthy participants (Figure 3.2B).

Significant correlation coefficients (r) and proportion of variance explained (r^2) by the variables for knee proprioception, ROM for knee flexion and extension, flexibility of the hip and ankle, and lower limb strength measurements with the three YBT reach directions are reported (Table 3.4). For the healthy subjects, knee-flexion ROM had a weak positive correlation with the ANT and PL, while hip flexibility had a weak positive relationship with the PM and PL. Several positive relationships between strength measures and the posterior reach directions were noted. Strength in knee flexion, knee extension and hip abduction had moderate correlations and hip

external rotation and ankle plantarflexion had weak correlations with the PM. Knee extension and hip abduction were moderately correlated and knee flexion and hip external rotation were weakly correlated with the PL. For ACL-injured subjects by comparison, there was a moderate positive correlation between hip flexibility and the ANT, and a moderate negative correlation between strength in knee flexion and the PL.

5. Discussion

To our knowledge, this investigation is the first to assess relationships of a wide range of anthropometric and lower limb characteristics with YBT measures of dynamic balance in an at-risk healthy adolescent female population, and an exploratory group of ACL-injured adolescent females. The main findings were that YBT reach distances did not differ between healthy and ACL-injured subjects. However, the correlations among anthropometric and lower extremity variables differed between the healthy and ACL-injured. In healthy subjects, weight and BMI had a moderate inverse relationship with the YBT posterior reach distances, and lower extremity strength was positively correlated with PM and PL. Weak relationships were observed for knee-flexion ROM with the ANT and PL, and hip flexibility with the PM and PL. For the exploratory group of ACL-injured subjects, there was no relationship between the anthropometric characteristics and the YBT. Hip flexibility had a moderate positive correlation with the ANT, and knee-flexion strength had a negative correlation with the PL.

Demographic findings confirmed that participants were representative of a typical adolescent female population that participates in a variety of recreational sporting activities and is nearing or has recently reached physical maturation. This is the feature that distinguishes the current study from all other reports on dynamic balance, and thus serves to fill an important gap in the

literature, as previous reports focused on athletes from specific sports[47,49], older age groups[45,258,289], or competitive levels[44,286]. Anthropometric measurements did not differ between healthy and ACL-injured groups even though the ACL-injured group was significantly older (by 2 years) than the healthy group.

The ability of surrounding musculature and other structures to compensate for the loss of support from an ACL injury determines the functional stability of the knee joint[102]. Results of the Pedi-IKDC and PAQ-A indicate that ACL-injured subjects reported deficits in knee function and ongoing knee symptoms yet continued to lead a relatively active lifestyle compared to healthy individuals. Lower extremity injuries, especially to the ACL, are at epidemic levels in the active adolescent female population[29,288,298], so it is essential to develop or find effective clinical measures of dynamic balance for use in screening athletes. Dynamic postural stability requires sensory information from proprioceptive, vestibular and visual systems to contribute to appropriate motor responses[295–297]. These systems are still developing during adolescence[154,297], which may reduce performance measured using clinical dynamic balance tests. Differences in the rate of development between males and females may also contribute to the particularly high gender-specific risk of ACL injuries in adolescent females[154,297,312,330]. Interestingly, older female adults also demonstrate deficits in dynamic postural stability due to the biological aging process[305], which may explain why the YBT reach distances of our adolescent females were similar to those of older adult females in an earlier report[309]. Our results provide important findings on the performance of healthy, recreationally active adolescent females on the YBT, information that was previously missing from the literature.

Interestingly, the finding that reach distances did not differ between healthy and ACL-injured subjects is contradictory to previous reports[267,268,296,318]. While ACL-injured participants have demonstrated deficits in dynamic balance compared to their uninvolved limb[267,296] and to asymptomatic controls[268,318], once again those investigations did not assess adolescent females. Rather, they included predominately male subjects from 20-40 years-of-age, with a longer time between injury and testing [11.2± 2 months (range, 0.4-24)[318], 12.8±3.9 months (range, 9-24)[296] and 17.3±12 months (range, 5-55)[267]] compared to the present report. While one study[268] assessed younger adult female athletes (control: 20.8±1.1 years; ACL-injured: 23.0±3.4 years) all the ACL-injured participants had received surgical stabilization (ranging from 10 months to 6 years) and rehabilitation prior to testing. Dynamic balance in that report was also assessed using different clinical (SEBT)[267,268,318] and laboratory (force plates)[296] methods than our study. However, based on our results from a population of 10 ACL-injured participants, future investigations with a larger sample size, more consistent injury-to-testing intervals, and similar test methods are encouraged to confirm and extend this research.

Physical measures of lower extremity proprioception, ROM, flexibility, and strength in this study were comparable with previous findings[303,322,331]: however, direct comparison is limited due to a deficiency of normative data for the specific age and gender of our population, different outcome measures and variations in the units reported in different studies. Healthy and ACL-injured subjects had similar measures of lower extremity parameters, except for knee-flexion ROM and hip-abduction strength. However, the difference was not considered to affect the other testing procedures, since both groups achieved knee-flexion ROM in the normal range[332(p12)]. Knee and hip musculature provide dynamic stability and kinematic alignment to the knee joint. Gender and

maturation both contribute to the deficiencies in knee extension, knee flexion and hip abduction and imbalances associated with ACL injury[333–337]. A longitudinal study by Quatman-Yates et al.[333] identified that strength deficits for hip and knee musculature emerge at different times during maturation. When females transition from pre-pubertal to pubertal status, hip abductor strength rapidly decrease relative to body mass, while knee flexor and extensor strength imbalances emerge gradually over a 3-year period[333]. This may explain why we observed differences in hip abduction strength between the two groups of subjects, when knee strength in extension and flexion did not differ. Future investigations with a longitudinal design could assess whether differences were due to the state of maturation or injury in the subjects.

Laboratory measures of dynamic balance are well-established to show a negative correlation with body weight[299–301]. The current investigation is one of the first to demonstrate a similar inverse relationship between weight, BMI, and a clinical measure of dynamic balance. Our results showed weight and BMI had moderate negative relationships with the PM and PL. These results may relate to the role of the hip and trunk in controlling lateral body sway to maintain postural stability[299]. A previous kinematic analysis of the YBT indicated that greater trunk flexion, trunk contralateral bending and hip flexion are required in posterior than anterior reach directions[302]. Thus, individuals with a greater BMI may have less lateral stability when extending to the limits of their base of support in posterior directions, and this may in turn influence their reach-distance performance. Anatomical distribution of adipose tissue mass, concentrated in the thorax-abdomen (android type) compared to the hip and thigh area (gynoid type) may contribute to lower YBT scores, and should be considered in future investigations.

Although deficits in balance and strength are associated with increased incidence of lower extremity injury, significant correlations between variables of strength and postural control have not been reported[304,305]. Findings on healthy subjects, that lower extremity strength measures had weak-to-moderate positive correlation with the PM and PL reach directions, are only partially consistent with reports for other populations. In female collegiate athletes, weak correlations between hip abduction strength with the SEBT PL[307] and between hip external rotation strength with the SEBT PM[306] are reported. Adult women demonstrate weak correlations between the strength of hip extensors, hip abductors, and knee flexors with YBT reach directions[308,309], including ANT[307,308]. Notably, correlations in the present study were confined to the two posterior reach directions, likely related to distinctive input in each direction. When reaching in the ANT direction, subjects receive visual feedback on their own performance. In PM and PL directions, visual awareness is lower and dynamic balance relies more on non-visual somatosensory systems. Since adolescents rely more heavily than adults on visual cues because pubertal growth reportedly inhibits some sensorimotor functions of the lower extremity[154], the variation in relative afferent inputs between adolescents and adults may explain these differences between current findings and previous reports in older populations.

Previous research suggests that the single best kinematic predictors for performance in each reach direction were ankle dorsiflexion ROM for ANT[302,303], and hip flexion strength for PM and PL[268,302]. Knee flexion ROM has also been moderately correlated with all three reach directions[302]. Surprisingly there was no relationship between ankle dorsiflexion ROM and performance in ANT, again likely due to differential influences of age and sex on flexibility. However, the weak relationships observed for knee-flexion ROM and hip flexibility are

consistent with previous reports and suggest further study of the impact of ankle ROM on YBT performance is warranted in adolescent females.

We specifically choose subjects to address an important deficiency in our ability to interpret results of clinical dynamic balance testing on recreationally active female adolescent athletes. However, while filling this gap, the external validity of current results is limited: an *a priori* analysis indicated that data for 22 subjects would power the planned assessment of dynamic balance tests in healthy individuals[48,289], while age, gender, and activity-level inclusion criteria limited recruitment to only 10 subjects to represent ACL-injured individuals. Future studies will need more subjects to establish normative values for ACL-injured, recreationally active adolescent females. Other measures such as isokinetic strength, muscle onset time, and muscle recruitment order will provide further insight into the important relationships between lower extremity muscles and dynamic balance in adolescent females.

6. Conclusion

Adolescent females participating in sports have notable risk of sustaining an ACL injury. The YBT is a common clinical screening tool for dynamic balance performance, risk of injury and tracking progress in recovery from ACL injury. This study was designed to bridge the absence lack of information about relationships between anthropometric and lower extremity variables and YBT performance in adolescent females. Anthropometric measures (weight and BMI) and lower extremity strength showed negative and positive correlations, respectively with performance in healthy individuals. These relationships were absent for ACL-injured subjects, while hip flexibility and knee-flexion strength were positively and negatively correlated with aspects of YBT performance. Results indicate that clinicians may consider emphasizing

improvements in these modifiable components of flexibility and knee-flexion strength to enhance YBT performance, and potentially decrease the risk of ACL-injury for active adolescent females. Further investigations of the differential performance related to physical and somatosensory maturation contributions to dynamic balance are needed to understand basis of postural performance.

7. Chapter 3 Tables and Figures

Table 3.1: Anthropometric and demographic information (mean ± SD) for healthy and ACL-injured groups, including assessments with the Pubertal Maturation Observational Scale (PMOS), the International Knee Documentation Committee (pediatric modification, Pedi-IKDC) scale, and the Physical Activity Questionnaire for Adolescents (PAQ-A).

	Healthy (n=25)	**ACL-Injured (n=10)**	**P value**
Age (years)	14.0 ± 1.3	16.3 ± 1.6*	< 0.001
PMOS, n (%)			
Pre-pubertal	3 (12)	0 (0)	
Mid-pubertal	5 (20)	4 (40)	
Post-pubertal	17 (68)	6 (60)	
Height (cm)	163.1 ± 5.8	165.5 ± 6.2	0.29
Weight (kg)	59.7 ± 15.5	68.0 ± 14.2	0.15
BMI (kg/m^2)	22.3 ± 4.8	24.8 ± 4.6	0.18
Leg Dominance – Right, n (%)	22 (88)	9 (90)	
ACL Laxity (mm)	6.5 ± 2.6	11.7 ± 1.7*	< 0.001
Time since injury (months)	-	4.7 ± 3.1 (range 0.8 – 12.0)	-
Pedi-IKDC (max score 100)	95.9 ± 9.8	63.5 ± 10.1*	< 0.001
PAQ-A (max score 5.0)	2.9 ± 0.8	2.4 ± 1.0	0.08
Sport (n)			
Basketball	1	3	
Badminton	1	0	
Baton	4	1	
Dance	4	0	
Cross country running	1	0	
Gymnastics	2	0	
Hockey/Ringette	5	1	
Rugby	0	1	
Soccer	2	1	
Softball	1	0	
Tennis	1	0	
Volleyball	3	3	

* $P < 0.05$

Table 3.2: Y-Balance Test (YBT) measures for anterior (ANT), posteromedial (PM), and posterolateral (PL) reach directions in healthy and ACL-injured subjects (mean ± SD)

	Healthy (n=25)	**ACL-Injured (n=10)**	**P value**
YBT – ANT (%LL)	65.6 ± 5.1	63.8 ± 5.1	0.34
YBT – PM (% LL)	100.5 ± 7.1	96.1 ± 8.9	0.13
YBT – PL (%LL)	98.5 ± 7.8	95.3 ± 7.6	0.27
* P < 0.05			

Table 3.3: Proprioception, ROM, flexibility, and strength measures for the lower limb in healthy and ACL-injured subjects (mean ± SD)

	Healthy (n=25)	**ACL-Injured (n=10)**	**P value**
Knee proprioception (Δ°)	2.8 ± 1.4	2.8 ± 2.1	0.96
Range of Motion – Knee Flexion (°)	146.3 ± 7.5	136.3 ± 7.0*	<0.001
Range of Motion – Knee Extension (°)	-1.8 ± 2.3	-0.7 ± 1.6	0.16
Flexibility – Hip (cm)	6.9 ± 11.7	5.3 ± 10.1	0.71
Flexibility – Ankle (cm)	11.5 ± 3.2	11.4 ± 3.3	0.96
Strength – Knee Flexion (N/kg)	3.3 ± 0.7	2.9 ± 0.8	0.17
Strength – Knee Extension (N/kg)	5.1 ± 1.2	4.7 ± 1.3	0.49
Strength - Hip External Rotation (N/kg)	2.0 ± 0.4	1.7 ± 0.5	0.15
Strength – Hip Abduction (N/kg)	1.8 ± 0.4	1.5 ± 0.3*	0.01
Strength - Ankle Plantarflexion (N/kg)	5.7 ± 1.2	5.1 ± 1.2	0.18

* P < 0.05

Table 3.4: Significant coefficients for correlation (r) and proportion of variance (r^2) for linear regressions between physical measures and normalized distance in anterior (ANT), posteromedial (PM) and posterolateral (PL) reach directions of the Y-Balance Test (YBT) for heathy and ACL-injured subjects.

YBT	Physical Measures	Correlation coefficient (r)	Proportion of variance (r^2)
Healthy Participants (n = 25)			
ANT	Range of Motion – Knee Flexion (º)	0.45*	0.20
PM	Flexibility – Hip (cm)	0.42*	0.17
	Strength – Knee Flexion (N/kg)	0.54**	0.29
	Strength – Knee Extension (N/kg)	0.52**	0.27
	Strength - Hip External Rotation (N/kg)	0.45*	0.20
	Strength – Hip Abduction (N/kg)	0.50**	0.25
	Strength - Ankle Plantarflexion (N/kg)	0.39*	0.16
PL	Range of Motion – Knee Flexion (º)	0.48*	0.23
	Flexibility – Hip (cm)	0.48*	0.23
	Strength – Knee Flexion (N/kg)	0.47*	0.22
	Strength – Knee Extension (N/kg)	0.53**	0.28
	Strength - Hip External Rotation (N/kg)	0.48*	0.23
	Strength – Hip Abduction (N/kg)	0.62**	0.38
ACL-Injured participants (n=10)			
ANT	Flexibility – Hip (cm)	0.66**	0.43
PL	Strength – Knee Flexion (N/kg)	-0.65**	-0.42

*r = 0.25-0.49 represent a weak correlation; **r = 0.50-0.74 represent a moderate correlation; *** r = 0.75-1.0 represent a strong correlation; $P < 0.05$ for all values

Figure 3.1: Y-Balance Test (YBT) for the left stance limb for the A. anterior (ANT), B. posteromedial (PM), and C. posterolateral (PL) reach direction.

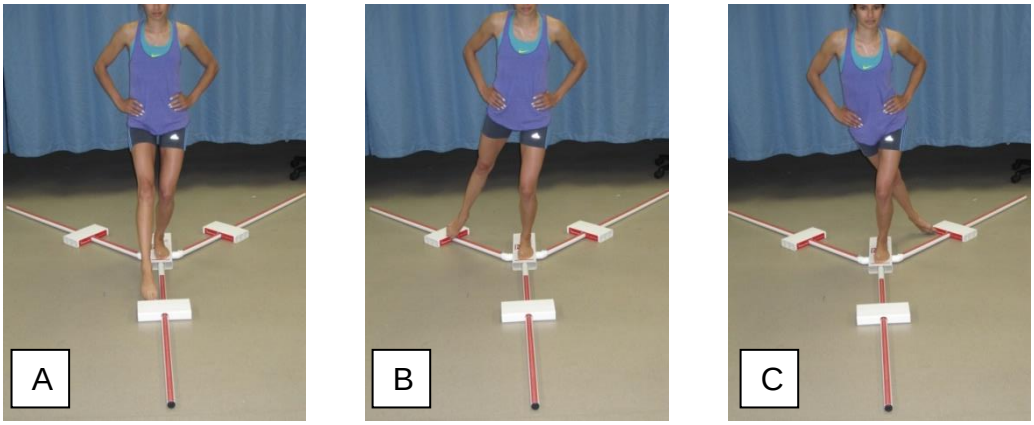
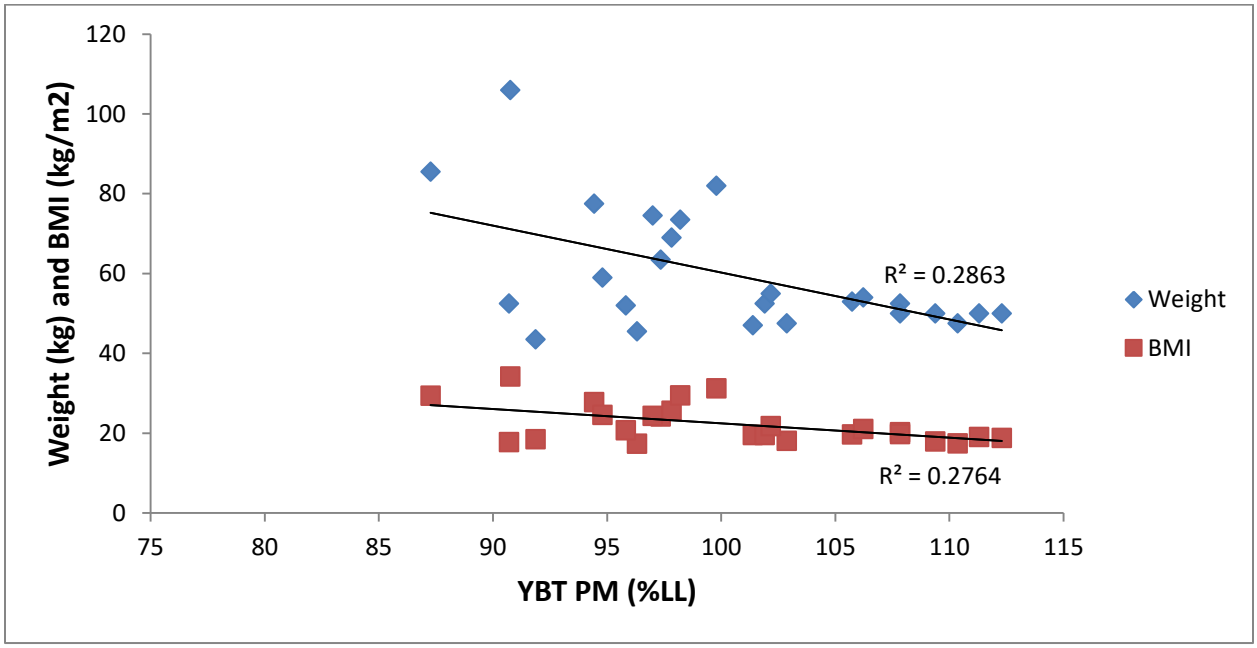
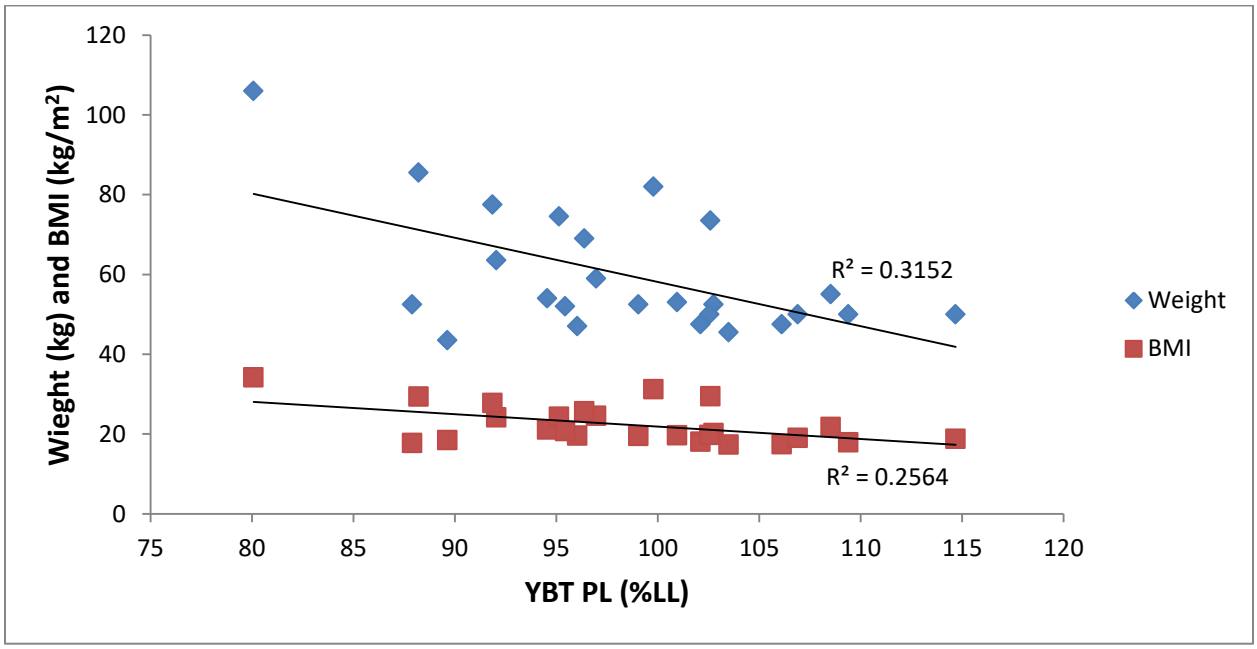


Figure 3.2: Simple linear regression between weight and BMI with the A. posteromedial (PM) and B. posterolateral (PL) reach directions of the YBT.





Chapter 4 – Lower Limb Kinematics of the Y-Balance Test Anterior Reach Direction in Adolescent Females

1. Abstract

Background: Adolescent females are at significant risk for sustaining ACL injury. Movement assessment via video analysis in a clinical setting can provide a reliable and valid measure of lower limb motion. The Y-Balance test (YBT) is a common clinical assessment tool used to evaluate lower limb dynamic balance. However few studies have quantified lower limb kinematics associated with performance of the YBT, and there is currently no kinematic data available for a physically active adolescent female population. *Objectives:* To perform a kinematic assessment of the lower limb in healthy and ACL-injured adolescent females when performing the anterior reach movement of the YBT. *Study Design:* Prospective cohort. *Methods:* Twenty-five healthy subjects and an exploratory group of 10 ACL-injured adolescent females were recruited. Participants were video-taped while performing the anterior reach movement of the YBT. Ankle dorsi-flexion and knee flexion angle were quantified in the sagittal plane. Knee valgus angle was measured in the frontal plane. YBT anterior reach distances and the kinematic angles between the healthy and ACL-injured subjects were compared. ANOVAs with a post hoc Bonferroni correction were used to compare the subjects grouped by reach distance. Single-subject analysis of all joint angles was also conducted. The relationship between kinematic angles and the YBT scoring was evaluated using Pearson product-moment correlations. *Results:* Healthy and ACL-injured subjects demonstrated similar reach distances and lower extremity kinematic angles. Healthy subjects demonstrated a weak positive correlation between the degree of ankle dorsiflexion and YBT reach distance, and a weak negative correlation with the degree of knee valgus and YBT scoring. These relationships did not exist for ACL-injured subjects. When data was organized by scoring on the YBT, analysis failed to reveal a significant difference in lower limb movement patterns. *Conclusions:* Video analysis and quantification of joint movements during execution of the YBT suggests that there is little

relationship between anterior reach distance measures and ankle dorsiflexion, knee flexion, or knee valgus angles. Furthermore, a variety of joint movement strategies can be used to perform a maximal reach distance on the. Future prospective kinematic investigations of healthy and ACL-injured adolescent females performing the YBT should examine the positions of the hip joint and trunk.

Key Words: anterior cruciate ligament, dynamic balance, 2D video analysis

2. Introduction

The anterior cruciate ligament (ACL) is one of the most common sites of orthopaedic injury, with an annual incidence of 68.6 per 100,000 person-years in the general population[2]. The majority of ACL injuries occur via a non-contact mechanism, when a sharp deceleration or pivoting manoeuvre applies an excessive valgus load and rotatory force to a knee, at or near full extension[338]. While risk of ACL injury is significant for both sexes, adolescent females have a 1.6-fold greater rate of ACL injury per athletic exposure than adolescent males[3,4]. In females, the peak incidence (227.6 per 100,000) of ACL injury occurs between 14-16 years of age[2]. Research seeking to explain this gender disparity has recently focused on modifiable biomechanical and neuromuscular factors that may influence the performance of functional tasks such as running and jumping, rather than anatomical and hormonal influences on the ACL[35,49,157–159]. Initial investigations suggest that adolescent female athletes demonstrate altered knee kinematics and deficits in postural stability as compared to males[35,49,157–159,339].

Two -dimensional (2D) video assessment has also been validated as a reliable tool for objectively evaluating lower limb motion in both the sagittal and frontal planes as part of a clinical assessment of the lower extremity[340–346]. Dynamic knee valgus measures have demonstrated to be predictive of ACL injury[158], and thus measurement of knee kinematics such as the knee valgus angle are of particular interest to clinicians[347–349]. Beyond this, the dynamic knee valgus angle has also been demonstrated to influence ankle joint kinematics[350,351]. Lower extremity kinematics are commonly assessed during the performance of functional tasks such as a single-leg squat, lateral step-down and various jump landings that are completed as part of pre-season or return to sport assessment[339,340,347,348,351]. However, there is limited data available

regarding lower limb kinematics which are associated with performance of dynamic balance tests[42,268,352,353].

Dynamic balance tests such as the Y-Balance Test (YBT)[38,39] and Star Excursion Balance Test (SEBT)[36,37] are commonly used in clinical and research settings to assess lower extremity function. Performance on these tests is quantified as a measure of maximal reach distance in a specific direction, or as a calculated composite score (average distance of all reach directions)[354]. Dynamic balance tests are used as a functional screen to identify athletes at potential risk of injury; to assess deficiencies following injury; or to monitor rehabilitation progress[35]. Lower test scores have previously been associated with an increased risk of ACL injury[43,47,285,286], ACL-deficiency[35] and following surgical repair[268]. Neuromuscular education and balance training programs have been reported to improve scoring on dynamic balance tests[49,355]. To date, few investigators have examined whether a link exists between performance on dynamic balance testing and kinematic measures of the lower extremity[42,268,352,353].

The purpose of this investigation was to perform a kinematic evaluation of the knee and ankle joints during execution of the YBT in healthy and ACL-injured adolescent females. The study had the following specific aims: 1. Quantify the reach distance of physically active adolescent females when performing the anterior reach of the YBT; 2. Quantify the degree of knee joint flexion, ankle joint dorsiflexion, and knee joint valgus when performance the anterior reach of the YBT; 3. Examine the relationship between knee and ankle joint kinematics and scoring for the anterior reach of the YBT; and 4. Compare the kinematic data and anterior reach scoring on the YBT between healthy and ACL-injured adolescent females. The hypothesis was that: 1)

Healthy and ACL-injured adolescent females would differ in their anterior reach distances; and 2) YBT reach distance would be influenced by kinematic profiles and movement strategies.

3. Methods

3.1 Participants

Following institutional ethics approval (H2014:302), healthy and ACL-injured adolescent females were recruited from the community to participate in this clinical study. Twenty-five healthy adolescents and an exploratory group of 10 ACL-injured subjects, and their parents, consented to participate. Healthy subjects reported no recent trauma to the lower extremity; subjects in the ACL-injured group had their injury confirmed via orthopaedic consult and magnetic resonance imaging. All participants were female, 12-18 years of age, with no history of lower limb injury (other than ACL trauma in the injured group) or concussion in the past 6 months. The height, weight, and BMI of all subjects were recorded. ACL laxity for all subjects was evaluated using the KT-1000 (MEDmetric Corp., San Diego, CA)[356]. Maturation status was determined using the self-reported pubertal maturation observational scale (PMOS)[357]; leg dominance was determined by preference for kicking a ball; and the types of sport participation for each participant was documented.

3.2 Testing Protocol

YBT Anterior Reach

All subjects completed the YBT (Move2Perform, Evansville, IL) according to previously described and standardized procedures[38]. For the purpose of this investigation, only the anterior reach direction was video-taped and used for subsequent analysis. Pilot testing demonstrated that

this reach direction provided a more consistent measure of kinematic angles and has been previously reported to be a significant discriminator in predicting risk of lower extremity injury[47,285,286]. Subjects were tested while barefoot with their hands on hips (Figure 1A &B). The reach distance was normalized as a percentage of each participant's stance-limb length (%LL). Limb length was measured from the anterior superior iliac spine to the most distal aspect of the ipsilateral medial malleolus in a supine, lying position[36].

Kinematic Analysis

Kinematic data from two video cameras (Sony Handycam HDR-UX20, Sony Corp., Minato, Toyko, Japan) was collected during one test trial for the anterior reach direction of each participant. One camera was positioned 3 meters in front of each subject to capture a full frontal-plane view, and the other was positioned 3 meters lateral to each subject to capture a sagittal view. All digital images were coded and saved for subsequent video analysis. Analysis was only completed on the dominant limb of the healthy subjects and the injured limb of the ACL-injured participants[255,267].

Open-license video analysis software (Kinovea 0.8.15) was used to kinematically quantify three joint angles at the point of maximal anterior reach distance when performing the YBT: 1. the degree of knee joint flexion in the sagittal plane; 2. the degree of ankle joint dorsiflexion in the sagittal plane; 3. the knee valgus angle in the frontal plane. Landmark selection was based on methodologies previously reported in the literature[358–360]. The same anatomical landmarks were used as reference points for calculating the joint angles of each participant. Relative angles were measured between limb segments created by joining the landmarks (Figure 1A&B). Reported

joint angles were calculated as the deviation of the relative angle from a neutral (anatomical) position (joint angle = neutral position – relative angle). The relative angle of knee flexion in the sagittal plane was determined by measuring the angle created between the lower leg and the posterior thigh with neutral being considered full extension (180°). The relative angle of ankle dorsiflexion in the sagittal plane was determined by measuring the angle created between the foot and the lower leg with neutral being considered 90° of flexion. The relative angle of knee valgus in the frontal plane was determined by measuring the angle created between the lateral thigh and the lower leg with neutral being considered full extension (180°). With this orientation the knee valgus angle was reported as a positive value.

3.3 Statistical Analysis

A power analysis ($n=2\{(1.96+0.84)9.5/8\}^2$) from a previous study of healthy recreationally active adults being tested using the YBT indicated that a minimum 22 healthy subjects would be required to adequately power this investigation[48,289]. ANOVA testing was used to analyze for differences between the healthy and ACL-injured subjects on demographic, anthropometric, YBT reach distance and the kinematic angles. An alpha level of $P < 0.05$ was set to determine statistical significance. The relationship between kinematic angles and the YBT scoring was evaluated using Pearson product-moment correlations[41,42,282]. Correlation coefficients *(r)* of 0.25-0.49, 0.50-0.74, and 0.75-1.0 were considered to represent weak, moderate and strong relationships[280]. The 95% confidence interval (CI) for the YBT reach distance of the healthy subjects was used to group subjects for comparison. ANOVA testing between groups with a post hoc Bonferroni correction of $P < 0.0167$ were used to determine statistical significance. In addition, we performed single-subject analysis for each variable using the healthy subject 95% CI's for comparison.

4. Results

Results indicated that the ACL-injured group was significantly older than the healthy group (Healthy: 14.0±1.3 yrs; ACL injured: 16.3±1.6 yrs, $p < 0.001$). With the exception of ACL laxity (Healthy: 6.5 ± 2.6 mm; ACL-injured: 11.7 ± 1.7 mm, $p < .001$), there were no significant differences between the anthropometric measurements of the 2 groups. Results indicated that all participants had a normal BMI (Healthy: 22.3 ± 4.8 kg/m^2; ACL injured: 24.8± 2.6 kg/m^2, $p=0.18$), and were predominantly post-pubertal adolescents (Healthy: 68%; ACL injured: 60%) who participated in a variety of recreational sporting activities including basketball, volleyball, soccer, hockey, and dance.

YBT reach distance and lower extremity kinematic angles for all subjects are presented in Table 4.1. There were no significant differences in YBT reach distance or lower extremity joint angles when comparing healthy and ACL-injured subjects.

Table 4.2 data illustrates the relationship between the YBT reach distance and lower extremity kinematic angles. Pearson correlation coefficient testing for the healthy subjects suggested that there were weak correlations between the YBT reach distance and the angle of ankle dorsiflexion (positive), the angle of knee valgus (negative), and there was a trend towards a positive relationship with the angle of knee flexion. These relationships were only significant for ankle dorsiflexion angle and knee valgus angle. Analysis of the ACL-injured data indicated that there were no relationships between YBT reach distance and kinematic angles.

Based on the 95% CI for healthy subjects YBT reach distance, healthy subjects were organized into three groupings; above (72.5 ± 2.8 %LL), within (64.7 ± 1.5 %LL) and below (58.2 ± 3.3

%LL). A comparison of the groups indicated that there were no significant differences in kinematic angles (Table 4.3A).

Table 4.3B presents data for the ACL-injured subjects when organized into the same three grouping (above, within or below) based on the 95% CI for healthy subjects YBT reach distance. There were no differences in kinematic angles between the three groups.

The same three YBT grouping (above, within or below) for reach distance, where then used for single-subject analysis. Each participants kinematic angles were coded according to 95% CI for each respective joint; above (+), within (0) and below (-). Data presented in Table 4.4A&B illustrated that both healthy and ACL-injured individuals utilized a large variety of movement strategies when performing the YBT.

5. Discussion

This is the first investigation to examine lower extremity kinematics during performance of the YBT in at-risk healthy and ACL-injured adolescent females. Results suggested that there were no significant differences between the healthy and ACL-injured subjects on YBT scoring or lower extremity joint angles when performing the YBT. Data for healthy adolescents indicated that there was a relationship between scoring on the YBT and the angle of ankle dorsiflexion and the angle of knee valgus, but no relationship with the angle of knee flexion. Results for the ACL-injured group suggested there were no relationships between any ankle or knee joint angles and YBT scoring. Interestingly, grouping of subjects according to their performance on the YBT (above, within or below the 95% CI) failed to identify any consistencies between YBT scoring and lower extremity joint angles (for example: a girl who scored well on the YBT was just as

likely to have a large knee flexion angle as a girl that performed poorly). A similar result was observed when single-subject analysis was performed. These findings help to reinforce the notion that adolescent females utilize a variety of joint movement strategies when performing the YBT, and these results suggest that scoring on the YBT may offer limited insight into lower extremity joint kinematics when performing dynamic balance testing.

This investigation is among the first to report kinematic data about the YBT for an adolescent-female population that participates in recreational sporting activities and is nearing or has recently reached physical maturation. Data indicate that despite the healthy group being significantly younger, the only significant difference between the anthropometry of the two groups was ACL laxity due to the ACL deficiency in the injured group. Numerous studies have indicated that laxity does not correlate well to functional joint stability[94,176,296].

The results serve to extend the findings of previous investigations on dynamic balance which have focused on athletes from specific sports[47,49], older age groups[45,258,289], or competitive sport[44,286]. The current literature indicates that dynamic balance performance scores can vary greatly, and can be influenced by a host of factors including the methodological approach used for assessment[41,42], the precision of the value reported[45,48,287,295,330,361], and the sample population's age[45,258,289], sex[47–49,312,330], sport[47,49], and competitive level[44,274,286]. The YBT reach distances for our adolescent female population were slightly higher than those previously presented for adults[41,42,353], slightly lower than scores obtained for adolescent athletes of both sexes[44,362], and most similar to scoring from older female participants[307,309]. While our data are different from YBT scoring previously reported for a general population, these differences are most likely attributable to our study's target population. Maturation of proprioceptive, vestibular

and visual systems, which are all required for dynamic postural stability, are still developing during the adolescent period[154,295–297]. YBT data in this study of female adolescents was most comparable to scores previously reported for 70-80 year-old females. It is possible that gender and biological changes associating with the aging process have a significant effect on the neuromuscular function required for scoring on dynamic balance testing[305,309]. Thus, the performance of participants in this study falls within the range of expected scores based on their age, gender and competitive level. Caution should be used when comparing these data with previous reports for an adult population.

Kinematic data from this investigation provides important information about joint movement during the execution of the YBT for a population of adolescent females at significant risk for lower extremity injury. Sagittal plane data for the angle of ankle dorsiflexion[42,352,353] and the angle of knee flexion[42,268,352,353,363] were comparable to previous reports of dynamic balance testing. Within a general population, dorsiflexion angles typically range from 32° to 39° and knee flexion angles have been reported to range from 51° to 68°[42,268,352,353,363]. To date, only one investigation has examined the knee valgus angle (mean=14.15° ±8.36) during performance of the YBT. This study was completed using 3D motion analysis of physically active university students (22 men and 8 women) with a mean age of 22.7 ± 2.2 years[353]. Our data for knee valgus angle were significantly lower than values presented in this report, and much closer to values reported in another study which evaluated a single leg squat task in 30 physically active young females[347]. The differences between our knee valgus angle data and the previous investigations may be attributable to differences in age and gender of the test populations, or possibly differences in the methodological strategies employed in each study (3D vs 2D analysis).

This study also investigated YBT reach distance and lower limb kinematics in an exploratory group of ACL-injured participants. Data indicated that YBT reach distance and joint angles were not significantly different when comparing healthy and ACL-injured adolescent females. These findings may suggest that our ACL-injured subjects were able to use some form of neuromuscular control in order to compensate for their ligamentous instability in their knee. Previous research does suggest that a percentage of ACL-injured patients, often referred to as "copers", are capable of coordinating muscle activity to dynamically stabilize the knee and resume preinjury activities without episodes of the knee giving-way[99]. Having said this, our investigation of the YBT is the first to include ACL-injured individuals. Previous investigations of clinical dynamic balance using subjects with ACL injury have used less reliable dynamic balance testing protocols such as the Star Excursion Balance Test (SEBT)[35,267]. These studies found differences between the healthy controls and the ACL-injured participants for the anterior reach direction[35] and the composite score[267]. Although the YBT and SEBT testing protocols are similar, research suggests that the anterior reach distance performance and kinematic profiles of test subjects are different, and that each test imposes different neuromuscular demands and postural-control strategies on the subject[41,42]. Thus caution should be used when comparing results from the different forms of dynamic balance testing, and further dynamic balance research which targets ACL-injured subjects is required in order to help clarify inconsistencies, and determine whether a difference really exists between injured and healthy limbs during execution of the YBT.[35,267]

Research on an adult population has previously indicated that the best single kinematic predictor of YBT scoring in the anterior reach direction is the angle of ankle dorsiflexion[353,364]. Anterior reach scoring has also been reported to have a moderate correlation with the angle of knee flexion. To date, no significant relationship has been established between YBT scoring and the angle of knee valgus[353]. Our results for an adolescent female population echo the findings of these investigations. YBT scoring for healthy subjects was positively correlated with the angle of ankle dorsiflexion (ie. subjects who achieved greater ankle dorsiflexion were able reach further on the YBT). However, our data suggested that there was no correlation between knee flexion angle and YBT scoring, and that there was a negative correlation between a subject's knee valgus angle and their YBT reach distance (ie. subjects who demonstrated increased knee valgus when executing the YBT also lower test scores). Previous research also indicates that kinematic assessment of the knee joint within an adolescent female population may be more important than the ankle joint as females demonstrate a larger dynamic knee valgus position than males when performing functional tasks such as jump landing and single leg squats[184,191,365]. Dynamic knee valgus measures during these functional tasks are reported to be predictive of risk for ACL injury in adolescent females[157–159,339]. This corresponds to reports that lower YBT scores[43,47,285,286] and greater knee valgus angles[157–159,339] are associated with an increased risk of ACL injury. In contrast to the healthy subjects, our results for the ACL-injured participants suggested that there was no relationship between lower extremity joint angles and YBT scoring. While the large range in scoring and small sample size may have contributed to this finding, it is also possible that the ACL deficiency may have led to an increase in the valgus instability or subjects may have been more hesitant about allowing their knee to adduct when performing the YBT, as the typical non-contact mechanism of ACL injury involves excessive knee valgus forces[338]. As a

result, the ACL-injured subjects may have subconsciously utilized different movement strategies at the hip joint or within the trunk region to achieve similar reach distances while protecting their injured knee joint[268].

Surprisingly there were no significant differences in kinematic angles for both the healthy and ACL-injured groups that performed above, within or below the 95% CI for YBT. The subsequent single-subject analysis also revealed no trends in kinematic angles based on YBT reach distance. The sensorimotor system that regulates balance and postural awareness relies on information from the visual, vestibular and somatosensory subsystems[294]. However, pubertal growth is reported to inhibit the sensorimotor functions of the lower extremity and lead to awkward movement patterns[154]. The variability of movement strategies we observed may be attributed to the fact that our participants were still progressing through or recently completed the maturation process, and as such their neuromuscular control and intersegmental limb coordination were still developing[154]. During execution of the YBT, the only instructions given to subjects were to push the reach indicator as far as possible along the pipe in the anterior reach direction while maintaining a unilateral stance with their hands on hips. No tips on how to enhance performance were given[38,48]. Our kinematic data for individual subjects would seem to suggest that adolescent females use various movement strategies to achieve maximal reach distance, including ankle dorsiflexion, knee flexion and knee valgus. Standardized placement of hands on hips was used to minimize the influence of upper body strategy, although variations in hip and trunk movement were unavoidable. Balance-correcting strategies of the trunk and hip are often used to maintain one's center of mass over a base of support and prevent loss of balance during a lower limb reach[268,353]. Other investigations indicate that a similar anterior reach distance can be achieved by

either flexing the hip and knee of the stance limb, or creating a Trendelenburg position, adducting the hip of the stance limb to lengthen the reach limb[268]. Lack of stability at the trunk and hip is suggested to contribute to lateral trunk and Trendelenburg positions, and subsequently knee valgus[157–159]. Unfortunately in this study, hip and trunk kinematics were not collected as the video camera was positioned to collect information exclusive to the lower extremity. The involvement of trunk and pelvic positions together with those of the lower extremity could reveal the role of distinct or varied positional strategies in stabilization during YBT, and should be examined in future investigations.

It is also important to note that the use of 2D video analysis in this study restricted our analysis of lower extremity movement during execution of the YBT to only the anterior reach direction. Analysis of the posterior reach directions (posterolateral & posteromedial) are much more complex due to the additional rotational movements of the trunk and lower extremity, and thus requires more sophisticated 3D motion-capture equipment[42,366]. Beyond this, the data collection protocol employed for the present study restricted videotaping during each subjects testing session to only 1 trial. As data collection progressed, it became apparent that some subjects changed their movement strategies during execution of the YBT, shifting from a knee-varus to a knee-valgus position when moving from the start position to the maximal reach stance. Assessment of each test trial throughout the full range of movement (rather than at the maximal reach position) may have been a more accurate approach for identifying the interactions between joint positioning and scoring on the dynamic balance test.

6. Conclusion

Adolescent females are significantly at-risk for sustaining an ACL injury. Kinematic analysis of some functional tasks suggests that certain movement of the lower extremity are predictive of ACL injury or instability. However, limited evidence exists regarding the kinematic parameters of the lower extremity when performing dynamic balance testing such as the YBT. The results of this investigation suggest that healthy and ACL-injured adolescent female subjects demonstrated similar reach distances and lower extremity kinematic variables when performing YBT. Interestingly healthy subjects were the only subjects to demonstrate a relationship between scoring on the YBT and lower limb kinematics. Data highlighted the fact that both healthy and ACL-injured adolescent females utilize a wide range of movement strategies when performing dynamic balance testing. Future prospective, longitudinal investigations of both healthy and ACL-injured adolescent females should include assessment of the hip joint and trunk kinematics, as well as the posterior reach directions, during execution of dynamic balance testing such as the YBT.

7. Chapter 4 Tables and Figures

Table 4.1: Y-Balance Test (YBT) reach distance and kinematic angles for all participants [mean ± SD, (95% CI)]

	Healthy (n=25)	ACL-Injured (n=10)	P value
YBT reach distance (% LL)	65.1 ± 6.0 (62.6 - 67.6)	64.5 ± 5.5 (60.6 - 68.4)	0.80
Knee flexion angle (degrees)	66.4 ± 10.9 (61.9 - 70.9)	70.9 ± 9.2 (64.3 - 77.5)	0.25
Ankle dorsiflexion angle (degrees)	28.4 ± 4.6 (26.5 - 30.3)	27.2 ± 4.9 (23.7 - 30.7)	0.49
Knee valgus angle (degrees)	3.9 ± 6.4 (1.3 - 6.5)	5.2 ± 7.8 (-0.4 - 10.9)	0.61

*P < 0.05

Table 4.2: Relationship between Y-Balance Test (YBT) reach distance and kinematic angles

	Healthy (n=25)		ACL-Injured (n=10)	
	r	**P value**	***r***	**P value**
Knee flexion angle (degrees)	0.37	0.07	0.43	0.21
Ankle dorsiflexion angle (degrees)	0.42*	0.04	0.06	0.87
Knee valgus angle (degrees)	-0.40*	0.05	0.30	0.52

* P ≤ 0.05

Table 4.3A: Kinematic angles (mean ± SD) for healthy participants grouped according to the 95% Confidence Interval (CI) for the YBT reach distance.

	Above 95% CI (n=7)	Within 95% CI (n=11)	Below 95% CI (n=7)
Knee flexion angle (degrees)	70.3 ± 15.0	68.6 ± 6.3	58.9 ± 9.6
Ankle dorsiflexion angle (degrees)	30.0 ± 3.5	29.5 ± 3.0	25.1 ± 6.4
Knee valgus angle (degrees)	2.6 ± 8.9	3.5 ± 6.1	5.9 ± 3.8

ANOVA testing with a post hoc Bonferroni correction of P < 0.0167

Table 4.3B: Kinematic angles (mean ± SD) for ACL-injured participants grouped according to the 95% Confidence Interval (CI) for the healthy subject YBT reach distance.

	Above 95% CI (n=2)	Within 95% CI (n=4)	Below 95% CI (n=4)
Knee flexion angle (degrees)	81.0 ± 8.5	69.8 ± 5.7	67.0 ± 10.2
Ankle dorsiflexion angle (degrees)	32.0 ± 1.4	22.8 ± 4.6	29.3 ± 2.1
Knee valgus angle (degrees)	6.0 ± 14.1	5.5 ± 8.5	4.5 ± 6.4

ANOVA testing with a post hoc Bonferroni correction of P < 0.0167

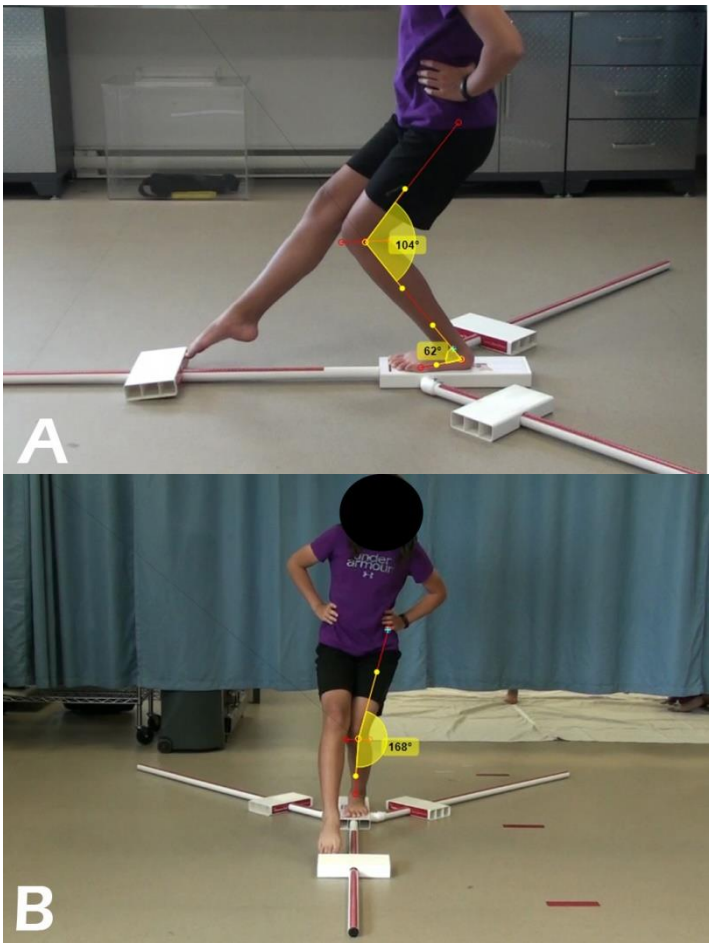
Table 4.4A: Results of single-subject analysis for healthy subjects grouped by Y-Balance Test (YBT) anterior reach performance in relation to the 95% CI calculated for healthy subjects; + indicates above 95% CI; 0 indicates within 95% CI; - indicates below 95% CI.

YBT	Knee flexion angle	Ankle dorsiflexion angle	Knee valgus angle
Above 95% CI	+	0	-
	+	+	0
	+	0	+
	-	0	-
	+	0	-
	0	+	+
	-	+	-
Within 95% CI	+	+	+
	0	0	0
	0	+	-
	0	+	0
	-	0	+
	+	0	+
	0	+	0
	+	0	-
	+	0	-
	0	0	+
	0	-	+
Below 95% CI	0	+	0
	+	-	0
	0	-	0
	-	-	0
	0	0	+
	-	0	0
	-	0	0

Table 4.4B: Results of single-subject analysis for ACL-injured subjects grouped by Y-Balance Test (YBT) anterior reach performance in relation to the 95% CI calculated for healthy subjects; + indicates above 95% CI; 0 indicates within 95% CI; - indicates below 95% CI.

YBT	Knee flexion angle	Ankle dorsiflexion angle	Knee valgus angle
Above 95% CI	+	+	+
	+	+	-
Within 95% CI	0	0	+
	+	-	+
	0	-	-
	+	-	0
Below 95% CI	-	0	0
	0	+	+
	+	0	-
	0	0	+

Figure 4.1: Y-Balance Test (YBT) for the left stance limb for the anterior reach direction, A. sagittal plane view with relative knee flexion and ankle dorsiflexion angles, B. frontal plane view with relative knee valgus angle.



Chapter 5 – Safety and Effectiveness of a Perturbation-based Neuromuscular Training Program on Dynamic Balance in Adolescent Females

1. Abstract

Background: Physically active adolescent females are at significantly greater risk for ACL injury than their male counterparts when participating in the same sports. Early surgical repair that includes some form of pre-operative rehabilitation has become the current standard of care. Preventative neuromuscular (NM) exercise programs are recommended to reduce injury rates and improve function. However, the safety and effectiveness of perturbation-based NM training in the at-risk adolescent female population has yet to be established. *Purpose:* To use a clinician friendly approach to examine the effectiveness of a perturbation-based NM training program on dynamic balance in healthy and ACL-injured adolescent females. *Methods:* Twenty-four healthy and an exploratory group of 10 ACL-injured females between the ages of 12-18 were equally randomized into a perturbation-based NM training or control group. Y balance testing, lower limb strength, proprioception and flexibility were measured before and after a 5-week perturbation-based NM training intervention. *Results:* The perturbation training program was safely completed by all participants but had no statistically significant effect on YBT composite scoring in either the healthy or ACL-injured groups. However, clinically significant improvements on YBT scoring by healthy participants was observed for the PM reach direction after subjects completed the perturbation-based NM training program. In healthy participants, hip abduction strength increased significantly following the intervention, while all other measures of lower extremity strength were unaffected in both groups. *Conclusions:* Perturbation-based NM training is safe, but offers limited benefit for healthy adolescent females and no preoperative benefit to ACL-injured adolescent females. Assessing other outcome measures and the ideal training volume for perturbation-based programs for this at-risk population will be an important area of future research.

Key words: anterior cruciate ligament; injury prevention; pre-operative rehabilitation; Y-balance test

2. Introduction

One of the most commonly observed and studied knee injuries in orthopaedic medicine are tears of the anterior cruciate ligament (ACL)[2]. While an ACL injury is a significant risk for both sexes, adolescent females have a 1.6-fold greater rate of ACL injury per athletic exposure than adolescent males[3,4], with the peak incidence of ACL injuries for females occurring between 14-18 years of age[2].

In North America, the standard of care for patients following ACL rupture is surgical reconstruction[14,15]. Early surgical reconstruction is especially favoured for adolescents vs. non-operative or delayed treatment, as it restores joint stability, reduces the incidence of secondary joint injury, and promotes return to previous levels of physical activity[227]. However, skeletal immaturity[15,17] and long surgical wait times[16] can both result in significant delays between the time of ACL injury and surgical reconstruction. In fact, the average wait time between ACL injury and surgery within a local regional health authority has been documented to be as high as 438 days[16]. Patients awaiting surgery are advised to participate in short-term, progressive exercise programs before[18,208] and after surgical repair[23,367] as they are thought to improve knee function. While there is some evidence to suggest that pre-operative rehabilitation is beneficial for ACL-injured subjects, there is limited information and a lack of consistency available to guide the type of exercise intervention, the duration of the intervention, or frequency of the programs.

Recently, the basis for the gender disparity in ACL injury rates among adolescents was explored by examining the neuromuscular (NM) and biomechanical factors that may influence the development of effective intervention strategies[35,49,157–159]. The objective of NM training is to

improve dynamic joint stability, generate fast and optimal muscle activation and decrease joint forces. Preventative NM training is recommended for all young athletes to reduce costs and morbidity from ACL injury[196]. In addition to reducing the rate of ACL ruptures in females adolescents by approximately 50%[29,30,32,197], incorporating preventative NM training during early adolescence can improve lower extremity performance[31,198], including dynamic balance[199–202]. While the specific training components included in the NM prevention programs can vary greatly, they typically include some combination of plyometric single-leg hops, jumps, pivoting and cutting maneuvers that are not practical or safe for the ACL-injured individual[29–32,197,198,203–207].

Perturbation-based NM training was designed to be safe and effective for the ACL-injured, physically active adult population[33]. It includes exercises in which the patient needs to maintain balance on a support surface while a clinician deliberately perturbs (i.e., manipulates) the support system[20]. Most published reports have evaluated the effectiveness of this program using knee kinematics and gait patterns[20–22,24,229,230,236,237]. To date, the safety and effectiveness of perturbation-based NM training on dynamic balance in the at-risk adolescent female population has gone unreported.

The Y-Balance Test (YBT) is a common functional assessment technique used for clinically assessing dynamic balance of the lower extremity[38,39]. It identifies athletes at risk of injury, is used to assess functional deficiencies after injury, and can help monitor progress in rehabilitation[35]. Scoring on the YBT is considered to provide a valid estimate of lower limb range of motion and flexibility, neuromuscular control, and strength[40,315]. Research suggests that

for the young athlete, scoring on dynamic balance tests such as the YBT has been significantly improved following the completion of a NM training program[199–202].

The purpose of this investigation was to test the safety and effectiveness of a perturbation-based NM training program on dynamic balance in adolescent females from a community based sport medicine clinic. Lower limb proprioception, flexibility, and strength were secondary outcome measures. Effects of the training on performance were assessed using healthy participants, and an exploratory group of ACL-injured adolescent participants. The hypothesis of this investigation was that completion of a perturbation-based neuromuscular exercise program would improve: 1) YBT reach distance scoring; and 2) Lower extremity physical measures such as proprioception, flexibility and strength in healthy and ACL-injured adolescent females. The results of this investigation are expected to provide researchers and clinicians valuable information potentially regarding ACL injury prevention in adolescent females and can be used to advance the current standard of care offered by local sport medicine clinics in the management of ACL-injured female adolescent patients awaiting surgery.

3. Methods

3.1 Participants

Twenty-four healthy adolescents and an exploratory group of 10 ACL-injured subjects were included in this study. Healthy subjects reported no recent trauma to the lower extremity; the ACL-injured group was evaluated clinically by an orthopaedic surgeon, and the diagnosis was confirmed via magnetic resonance imaging. Inclusion criteria stated that volunteers were required to be female, 12-18 years of age, with no history of any other lower limb injury or concussions in the past 6 months. Participants were excluded if they were unable to attend either

the testing or training sessions, or if they failed a standardized screening protocol at the beginning of the study. A participant was scored as a "failure" and excluded from study participation if they presented with knee joint effusion, were unable to fully flex and extend the knee joint, had quadriceps lag with an active straight-leg raise, had quadriceps strength less than 75% of the unaffected leg or were unable to perform 10 pain-free consecutive single-legged hops[33].

3.2 Testing Protocol

Following institutional ethics approval (H2014:302), healthy adolescent females were recruited from the community and ACL-injured adolescent females were recruited from a community based orthopaedic clinic to participate in this clinical study. A power analysis ($n=2\{(1.96+0.84)9.5/8\}^2$) from a previous study of healthy, recreationally active adults indicated that 22 healthy subjects would be adequate to assess dynamic balance[48,289]. Prior to starting study activities, informed consent was obtained from parents and participants. Anthropometric information including height, weight, and body mass index (BMI) were recorded. ACL laxity was evaluated using the KT-1000 (MEDmetric Corp., San Diego, CA)[356]. Demographic information, including age, maturation status determined using the self-reported pubertal maturation observational scale (PMOS)[357], leg dominance determined by preference for kicking a ball, and type of sport participation were collected. Proprioception, flexibility, strength, and dynamic balance of the lower extremity were measured before and after the intervention, for which each subject was randomized into a perturbation-based NM training or control group by opening a coded envelope.

Dynamic balance

The YBT was completed according to previously described protocols[38,368]. The distance from the YBT apex of the most proximal edge of the reach indicator was recorded. The average of 3 successful trails for each reach direction was used for analysis. All reach distances were normalized as a percentage of each participant's stance-limb length (%LL), measured from the anterior superior iliac spine to the most distal aspect of the ipsilateral medial malleolus in a supine, lying position[36]. Subsequent use of the terms ANT (anterior), PM (posteromedial) and PL (posterolateral) will refer to the normalized reach direction and distance achieved when performing the YBT.

Strength

Hand-held dynamometry (HHD) is a valid, reliable measure of isometric muscle strength in adolescents[327] and an ideal test method for use when evaluating lower extremity strength in a clinical setting[327,328]. The "make-test" method was used, as it is preferred for use with adolescents: the examiner held the dynamometry instrument (Chatillon DFX II Series, Largo, FL) stationary while the subject gradually built resistance for a 5-second push against the dynamometer[327]. Standardized positions were used to assess knee flexion, knee extension, hip external rotation, hip abduction, and ankle plantar flexion[329]. Three HHD measurements for each movement were averaged. Strength scores for each subject were expressed as HHD force (N) relative to body weight (kg).

Proprioception

Joint-position sense (JPS), the awareness of position in three dimensions, is a common test of proprioception, and incorporation of weight bearing (WB) tests provides a functional

evaluation[322] with greater clinical relevance[323] for conditions such as ACL-deficiency where instability is experienced in WB[324]. Following published procedures[322,323], WB-JPS was assessed by asking subjects to maintain a unilateral stance, with the untested limb lifted off the ground, and minimal bilateral hand support. With eyes closed, the subject was instructed to slowly flex the knee of the WB limb and to stop at approximately 30 degrees of flexion - the test angle (TA). An electro-goniometer (Acumar Dual Inclinometer ACU0002, Lafayette Instrument Company, Lafayette, IN) placed at the thigh and lower leg was used to evaluate the exact knee-joint angle. The TA was held for approximately 5 seconds before returning to an erect bilateral stance. The subject was then asked to reproduce the same amount of unilateral knee flexion, which is known as the response angle (RA). Absolute angular error (AAE) is a sign-less arithmetic difference between the TA and RA scores. The test was repeated 3 times, and the average for each limb was used for analysis.

Flexibility

Flexibility of the hip and ankle were measured using joint-specific tests, according to established protocols[303,325,326]. A standing toe-touch test was used to assess hip-joint ROM[325]. Subjects stood on a step-stool with their feet hip-width apart and were instructed to keep their knees, arms and fingers straight while they bent forward as far as possible. The maximum reach position held for a minimum of 6 seconds was measured to the nearest 0.5 cm; the average of 3 trails was used for analysis[325]. Ankle-joint flexibility was determined using the weight-bearing lunge test (WBLT)[303]. Subjects were instructed to keep their test heel on the floor while flexing their knee towards the wall in front of them, and asked to maximize the distance from the great toe to the wall (measured in cm) while maintaining heel and knee contact. After practising 3 times,

subjects had measurements collected for 3 test trails, the average of which was used for analysis[303].

Perturbation-Based NM Training

Participants completed two supervised perturbation-based NM training sessions per week, for five consecutive weeks (for a total of 10 sessions). This validated training program[18–27] was administered according to a previous report[33] (Appendix A). In brief, a series of destabilizing perturbations were applied to each of the involved and uninvolved legs during stance on each of three unstable surfaces (rockerboard, rollerboard and rollerboard/platform), both in bilateral and unilateral stance (Figure 5.1)[33]. Over the 5-week course of the program, application of the destabilizing force progressed from an informed unilateral direction, slow and low in magnitude, to an unexpected, rapid application of destabilizing forces in random directions with sport-related distractions (catch and throw a ball).

3.3 Statistical Analysis

Following recommendations of previous reports[267], the dominant limb was used to represent healthy participants and the affected limb was used to represent the ACL-injured participants. SPSS for Windows v24.0 (SPSS Inc., Chicago, IL) was used for analysis. One-way analysis of variance (ANOVA) was used to test the differences in baseline demographic and anthropometric data between perturbation and control groups for each of healthy and ACL-injured groups. Two-way ANOVAs were used to compare post- vs. pre-intervention differences in anthropometric characteristics, proprioception, flexibility, strength and dynamic balance. A *post hoc* Bonferroni correction of $P \leq 0.008$ was set to determine statistical significance. A Fisher's exact test was

used to examine the relationship between the group (control or perturbation training) and clinically significant improvements in each YBT reach direction. Based on a previous report, a clinically significant improvement was classified as greater than 6.8%, 8.1% and 7.1% for the ANT, PM and PL reach directions, respectively[289]. The level of significance was set at $P \leq 0.05$. The "number needed to treat" (NNT) for a subject to benefit from the perturbation training program was also calculated.

4. Results

Results from the initial test session indicated that there were no significant differences in the demographic and anthropometric data between groups, with the exception of age and ACL laxity. The ACL-injured control group was significantly older than both healthy- perturbation and healthy-control groups. ACL laxity for both of the ACL-injured groups was significantly greater than both of the healthy groups (Table 5.1). Over the duration of the study, there were no changes in weight, or BMI for any of the groups. Results suggested that participants in each group were predominantly post-pubertal adolescents who were right leg dominant and participated in a variety of sporting activities.

All participants completed both testing session, and the mean time from the initial to follow-up assessment was 41 days (range: 30-47). All subjects randomized to the perturbation group safely completed the training program without any incidence of pain, swelling or knee instability. The training program included 10 sessions - the mean number of completed sessions was 9 (range: 7-10). On average, the 10 NM training sessions were completed in 31 days (range: 21-35). For ACL-injured participants, the mean time from injury to the baseline examination was 143 days (range: 24-365).

A comparison of initial and follow-up test scores for the YBT are presented in Figures 5.2- 5.4. For the ANT direction, follow-up test scores of the healthy participants were significantly larger regardless of their grouping (Time effect: $P \leq 0.008$), while there was no significant change for the ACL-injured groups (Figure 5.2). Data for the PL & PM directions indicated that both the healthy and ACL-injured groups follow-up test scores were significantly larger then scoring from initial testing, regardless of whether participants completed the perturbation training (Time effect: $P \leq 0.008$) (Figure 5.3 & 5.4). In the PM direction, the ACL-injured control group reach distance was also greater at follow-up examination (Training effect: $P \leq 0.008$) (Figure 5.4).

The results of the Fisher's exact test and the number needed to treat (NNT) are presented in Table 5.2 (for the 24 healthy subjects) and Table 5.3 (for the 10 ACL-injured participants). PM reach direction data from YBT testing of healthy participants suggested that the perturbation training group was more likely to show a clinically significant improvement as compared to the control group ($P \leq 0.05$). For one healthy participant to improve their performance on the YBT in the PM reach direction, a minimum of 3 subjects need to complete the perturbation training program. For the ACL-injured subjects, no relationship was found for any of the reach directions.

Knee strength measurements for the healthy participants are presented in Table 5.4. The knee flexion strength for the perturbation group was significantly larger on follow-up testing, but significantly lower than control group at both initial and follow-up testing. Overall, strength in knee flexion, knee extension and hip external rotation each increased for both the control and

training groups, regardless of whether participants completed the perturbation training. Hip abduction strength decreased in the control group and increased for the training group.

Knee strength measurements for the ACL-injured participants are presented in Table 5.5. Knee flexion and hip external rotation strength increased for both the control and perturbation groups. When comparing initial and follow-up data, no significant differences in scoring for knee proprioception, flexibility of the hip joint, or flexibility of the ankle joint were observed within or between groups for both the healthy (Table 5.6) and ACL-injured participants (Table 5.7).

5. Discussion

This is the first investigation to examine the safety and effectiveness of a perturbation-based neuromuscular training program on dynamic balance in adolescent females. Our results suggest that participation in the perturbation training program was safe, but had no statistically significant effect on YBT performance in either the healthy or ACL-injured adolescent female participants. However, clinically significant improvements in YBT performance by healthy participants were observed for the PM reach direction after participants completed the perturbation training program. In healthy participants, hip abduction strength increased significantly following the perturbation training program, while all other measures of lower extremity strength were unaffected for both the healthy and ACL-injured participants. Knee proprioception and flexibility of the hip and ankle joints were unaffected by the training program. Results suggest that there are limited benefits associated with participation in a perturbation-based NM training program for healthy or ACL-injured adolescent females.

The results of the current investigation help to fill a gap in the literature regarding the safety and effectiveness of perturbation-based NM training in the at-risk adolescent female population that participates in recreational sporting activities. Research has previously established that YBT performance scores are significantly influenced by the sample population's age[45,258,289], sex[47–49,312,330], sport involvement[47,49], and level of competitiveness[44,274,286]. Beyond this, previous studies on perturbation-based NM training have solely focused on a physically active adult population[20–22,24,229,230,236,237]. Our demographic and anthropometric data suggested that the study sample was comprised of physically active females who participate in a variety of recreational sporting activities, who have normal body weight and physical stature, and have reached or are approaching physical maturity. The participants were representative of the studies target population - females who are either at-risk or have previously sustained an ACL injury. As such, the results are highly generalizable.

Previous investigations targeting a physically active adult populations have demonstrated the effectiveness of a perturbation-based NM training program[20–22,24,229,230,236,237]. A quadriceps-dominant muscular activation pattern (demonstrated in active healthy adult females), may underlie the higher risk of ACL injury in female athletes. Perturbation training has been used to eliminate an imbalance between quadriceps and hamstring performance in adult females and thus may be beneficial as an ACL injury prevention program for this demographic[236,237]. ACL-injured adult females also demonstrate improved gait and coordination after participating in a perturbation training program[20–22,24,229,230]. Although these results are encouraging for ACL injury prevention and rehabilitation in an adult population, the distinctive biomechanical development through adolescence puts adolescent females at greater risk of ACL injury. A recent

meta-analysis reported an age-related association between the outcomes of neuromuscular training and the risk of ACL injury, and highlighted the value of neuromuscular training in female athletes under 18-years-old[197]. Our investigation was necessary to determine if the positive effects of perturbation-based NM training demonstrated in an adult population would also be observed in adolescent females[369] who are at a high risk of ACL injury[2–4].

As all subjects randomized to the training group were able to complete the program without any incidences of knee joint pain, swelling or instability our data suggest that the perturbation training was safe. However, the perturbation training had no overall effect on YBT reach distances in our adolescent female population. Although, there were significant time effects for both groups (control and perturbation) that were observed at follow-up testing for a majority of the participants, the ANT reach direction of the ACL-injured group failed to show a significant change. Previous studies reported improvements in YBT scores after healthy youth athletes completed NM training[199–201]. Vitale et al. evaluated an 8-week program focused on core stability, plyometric and body-weight strengthening exercises[199]; two other studies assessed a 4-week[200] or 10-week[201] FIFA 11+ kids program which included 7 activities: a running game, two jumping exercises, a balance/coordination task, two exercises targeting body stability and an exercise to improve falling technique. Recent meta-analyses suggest that combining plyometric and balance exercises may maximize effectiveness of preventative NM programs for healthy adolescent females[204,207,209]. The present study used a perturbation-based NM program in isolation so both the preventative effects in healthy subjects and the rehabilitative effects in ACL-injured subjects could be assessed. Our results suggest that perturbation training alone, did not affect dynamic balance. Notably, plyometric exercises used in other NM programs may not

be safe or practical for ACL-injured subjects[228]. Thus, further research which examines the effectiveness of perturbation training programs using other outcome measures such as gait analysis or muscular reaction to an anterior tibial translation are warranted. Additionally, possible increases in the duration or frequency of the perturbation-based NM program should also be considered for an adolescent population.

Our data indicated that hip-abduction strength decreased in healthy control subjects. This is consistent with findings of a longitudinal study showing strength deficits of hip musculature (relative to body mass) emerge during a 3-year transitional period of pubertal maturation[333]. This decrease in hip muscle activity may be an important factor in the increased susceptibility of female athletes to non-contact ACL injuries[158,185,370], because decreased limb control may excessively load the limb in knee abduction (valgus) and in turn, increase ACL loading[333,338]. Alternatively, our data indicated that healthy subjects who completed the perturbation-based NM training demonstrated an increase in hip-abduction strength, suggesting it is effective for increasing hip strength and can possibly help to control abnormal movements (ie. knee adduction moments) of the lower extremity which may lead to ACL injury.

The goal of this study was to use clinician-friendly outcome measures to investigate the relevance and potential benefits of using a perturbation-based NM training for ACL injury prevention and rehabilitation programs. Results indicated that clinically significant improvements in the PM reach direction were likely due to the positive correlation between hip abduction strength and the PM reach direction of the YBT (which has been reported for both healthy adult[308] and adolescent females[371]). Interestingly, hip-abduction strength is also reported

to be the only significant predictor of YBT performance in healthy men and women[372]. Thus, the present finding of a clinically significant improvement may be linked to the increase in hip-abduction strength noted in our healthy subjects after perturbation training.

It is important to acknowledge that our study did have several limitations. First, our study utilized YBT testing protocols that were established for use in an adult population. A typical YBT protocol in adults involves four training trials and three test trials to report a reach distance as the average of the three test trials[38]. The few studies that have instigated YBT in an adolescent population report variations such as the average of the last 3 of 6 successful attempts[199], the best of 3 successful trails[200], or 1 practice and 2 test trials[201]. A recent study of only males recommended that 6 practice trails and 3 test trials should be performed in an adolescent population to increase the reliability of YBT assessments[373]. Further standardization of the YBT in the adolescent population is required to allow for accurate comparison between studies. A second limitation is that our *a priori* analysis indicated that 22 subjects would provide adequate power to assess dynamic balance[48,289]. The specific age, gender, and activity-level inclusion criteria limited our ACL-injured recruitment to an exploratory group of only 10 subjects. Finally, our data collection methods focussed exclusively on quantitative outcome measures. However, anecdotally many subjects commented on improvements in confidence levels and the ability to complete activities of daily living such as riding a bike or participating in physical education classes. The inclusion of valid and reliable subjective or psychological assessment tools would have potentially allowed our analysis to examine how participation in the perturbation training program may have influenced confidence, self-esteem, and overall quality of life of participants.

6. Conclusion

Data indicate that the perturbation training program was safe but had no statistically significant effect on YBT performance in either the healthy or ACL-injured adolescent female participants. However, clinically significant improvements in YBT performance by healthy participants were observed for the PM reach direction after participants completed the perturbation training program. In healthy participants, hip abduction strength increased significantly following the perturbation training program, while all other measures of lower extremity strength were unaffected for both the healthy and ACL-injured participants. Knee proprioception and flexibility of the hip and ankle joints were unaffected by the training program. Results suggest participation in only a perturbation-based NME training is safe for healthy and ACL-injured adolescent females, however offers limited benefits. Future research should be directed at examining whether perturbation-based NM training has a positive affect when combined with other forms of training currently used for preventative and pre-operative rehabilitation in the at-risk adolescent female population.

7. Chapter 5 Tables and Figures

Table 5.1: Demographic and anthropometric information for all subjects (mean ± SD)

	Healthy (n=24)		**ACL-injured (n=10)**	
	Control (n=12)	**Perturbation (n=12)**	**Control (n=5)**	**Perturbation (n=5)**
Age (years)	13.9 ± 1.1	14.3 ± 1.5	16.9 ± 0.9[a]	15.7 ± 2.0
Height (cm)	161.8 ± 6.2	164.5 ± 5.5	166.4 ± 6.1	164.5 ± 6.8
Weight (kg)	54.3 ± 10.8	63.3 ± 17.7	63.1 ± 16.9	72.9 ± 10.3
BMI (kg/m^2)	20.6 ± 3.2	23.3 ± 5.4	22.6 ± 4.9	26.9 ± 3.4
ACL Laxity Difference (mm)	1.5 ± 1.1	1.5 ± 1.0	5.1 ± 3.7[b]	5.0 ± 2.6[c]
Time since injury (months)	-	-	3.6 ± 2.1	5.9 ± 3.7
Leg Dominance – Right, n (%)	11 (92)	10 (83)	4 (80)	5 (100)
PMOS, n (%)				
Pre-pubertal	2 (17)	1 (8)	0 (0)	0 (0)
Mid-pubertal	3 (25)	2 (17)	2 (40)	1 (20)
Post-pubertal	7 (58)	9 (75)	3 (60)	4 (80)

[a]Significantly different than the healthy control (P<0.001) and healthy perturbation (P=0.002)
[b]Significantly different than the healthy control (P=0.006) and healthy perturbation (P=0.005)
[c]Significantly different than the healthy control (P=0.001) and healthy perturbation (P=0.001)

Table 5.2: Number of healthy participants having reached clinically significant improvements (P value[a] from Fisher's exact test) and number needed to treat (NNT) in each Y-balance test (YBT) reach direction.

YBT reach direction	Control (yes/no)	Perturbation (yes/no)	P Value[a]	NNT
ANT	2/10	3/9	0.50	12
PL	3/9	3/9	0.68	-
PM	0/12	4/8	0.05[b]	3

[b] Larger number in the perturbation- NM training group, P≤0.05

Table 5.3: Number of ACL-injured participants having reached clinically significant improvements (P value[a] from Fisher's exact test) and number needed to treat (NNT) in each Y-balance test (YBT) reach direction.

YBT reach direction	Control (yes/no)	Perturbation (yes/no)	P Value[a]	NNT
ANT	0/5	1/4	0.50	6
PL	2/3	2/3	0.74	-
PM	3/2	1/4	0.26	-2.5

Table 5.4: Strength measurements for the healthy subjects (mean ± SD)

	Control (n=12)		Perturbation (n=12)		P Value[a]	
	Initial	**Follow-up**	**Initial**	**Follow-up**	**Time**	**Time x Group**
Knee Flexion (N/kg)	3.7 ± 0.6	3.8 ± 0.6	2.9 ± 0.6[b]	3.3 ± 0.7	0.02[c]	0.11
Knee Extension (N/kg)	5.4 ± 1.3	5.8 ± 1.2	4.8 ± 1.1	5.5 ± 1.3	0.02[c]	0.52
Hip External Rotation (N/kg)	2.1 ± 0.5	2.3 ± 0.4	1.9 ± 0.3	2.0 ± 0.4	0.01[c]	0.48
Hip Abduction (N/kg)	2.0 ± 0.4	1.8 ± 0.3	1.7 ± 0.3	1.9 ± 0.4	0.86	<0.01[d]
Ankle Plantarflexion (N/kg)	5.9 ± 1.3	5.7 ± 1.2	5.7 ± 1.3	5.4 ± 1.3	0.43	0.82

[a] Findings from multivariate analysis of variance
[b] Lower than the Control initial (P=0.003) and follow-up (P=0.002) groups.
[c] Increased from initial to follow-up for all groups
[d] Control group decreased and perturbation group increased

Table 5.5: Strength measurements for the ACL-injured subjects (mean ± SD)

	Control (n=5)		Perturbation (n=5)		P Value[a]	
	Initial	**Follow-up**	**Initial**	**Follow-up**	**Time**	**Time x Group**
Knee Flexion (N/kg)	3.1 ± 1.1	3.6 ± 1.1	2.7 ± 0.3	3.0 ± 0.3	<0.01[b]	0.55
Knee Extension (N/kg)	5.0 ± 1.8	5.6 ± 1.4	4.5 ± 0.5	4.9 ± 0.8	0.09	0.77
Hip External Rotation (N/kg)	1.9 ± 0.7	2.1 ± 0.7	1.6 ± 0.2	1.8 ± 0.3	0.02[b]	0.91
Hip Abduction (N/kg)	1.5 ± 0.3	1.5 ± 0.3	1.5 ± 0.2	1.6 ± 0.3	0.37	0.44
Ankle Plantarflexion (N/kg)	5.4 ± 1.4	5.6 ± 1.1	4.8 ± 1.0	4.9 ± 0.6	0.51	0.82

[a] Findings from multivariate analysis of variance
[b] Increased from initial to follow-up for all groups

Table 5.6: Proprioception and flexibility measurements for the healthy subjects (mean ± SD)

	Control (n=12)		Perturbation (n=12)		P Value[a]	
	Initial	**Follow-up**	**Initial**	**Follow-up**	**Time**	**Time x Group**
Knee Proprioception (Δ°)	2.8 ± 1.2	3.3 ± 2.3	2.8 ± 1.7	3.3 ± 3.2	0.54	0.98
Hip Flexibility (cm)	5.6 ± 15.6	7.1 ± 15.5	8.2 ± 7.1	7.6 ± 9.1	0.61	0.25
Ankle Flexibility (cm)	11.3 ± 3.5	11.0 ± 3.5	11.8 ± 3.2	12.3 ± 3.2	0.85	0.43

[a] Findings from multivariate analysis of variance

Table 5.7: Proprioception and flexibility measurements for the ACL-injured subjects (mean ± SD)

	Control (n=5)		Perturbation (n=5)		P Value[a]	
	Initial	**Follow-up**	**Initial**	**Follow-up**	**Time**	**Time x Group**
Knee Proprioception (Δ°)	3.6 ± 2.1	2.1 ± 1.5	1.9 ± 1.8	3.3 ± 4.8	0.95	0.23
Hip Flexibility (cm)	1.1 ± 9.8	4.1 ± 7.6	9.5 ± 9.4	10.0 ± 6.6	0.31	0.44
Ankle Flexibility (cm)	13.4 ± 3.3	13.3 ± 4.1	9.4 ± 1.8	9.8 ± 1.8	0.51	0.33

[a] Findings from multivariate analysis of variance

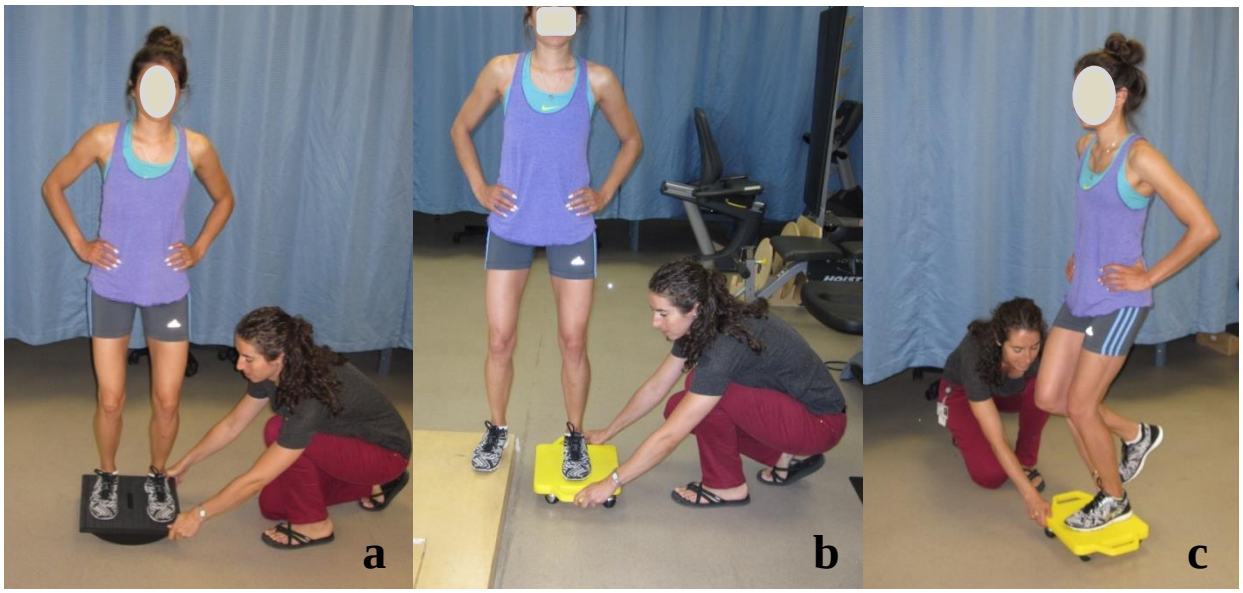


Figure 5.1: Perturbation-based NM training surfaces. a: Rockerboard; b. Rollerboard/Platform; c. Rollerboard.

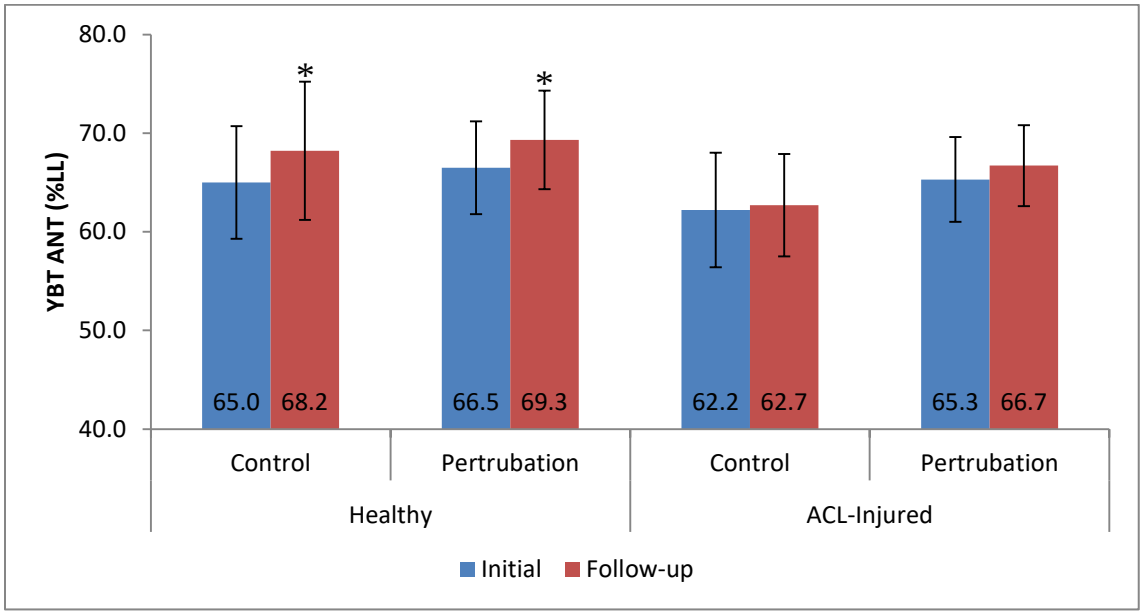


Figure 5.2: Performance changes on the YBT Anterior (ANT) reach direction for healthy and ACL-injured subjects (mean ± SD). Time effect:*P≤0.008 (Bonferroni correction).

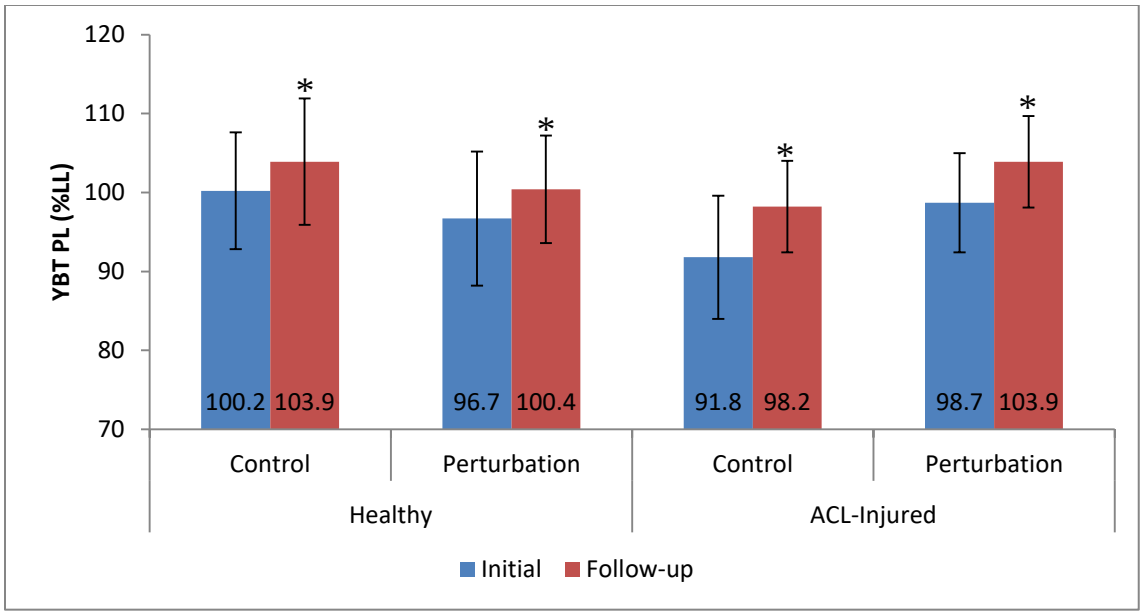


Figure 5.3: Performance changes on the YBT Posterolateral (PL) reach direction for healthy and ACL-injured subjects (mean ± SD). Time effect:*P≤0.008 (Bonferroni correction).

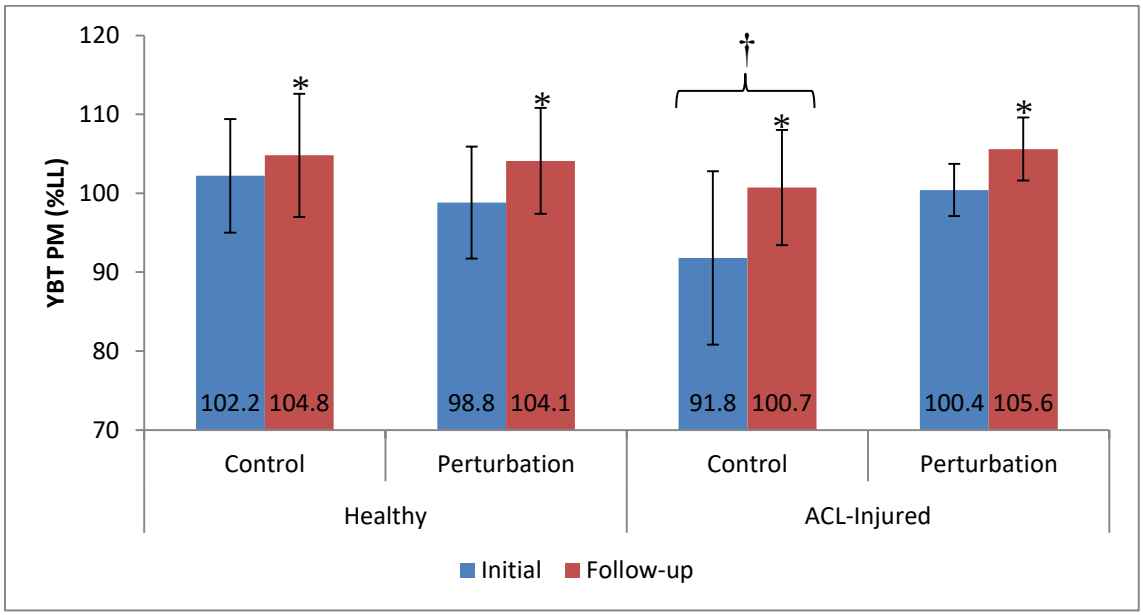


Figure 5.4: Performance changes on the YBT Posteromedial (PM) reach direction for healthy and ACL-injured subjects (mean ± SD). Time effect: *P≤0.008; Training effect: †P≤0.008 (Bonferroni correction).

Chapter 6 – General Discussion

1. Summary

This four-part research project used an evidence-based approach to investigate the scoring and performance of clinical dynamic balance tests and the effectiveness of a perturbation-based neuromuscular exercise training program in healthy and ACL-injured adolescent females. The goal of this project was to provide researchers and clinicians with information which could potentially advance the current standard of care used in the assessment, prevention and pre-operative management of ACL injuries in adolescent females.

The first portion of the thesis (Chapter 2) investigated two commonly utilized clinical dynamic balance tests, the SEBT and YBT, in a healthy adolescent female population. Findings indicate that participant scoring for the three similar reach directions differ between the test methods. The anterior reach distance was greater for the SEBT than the YBT; interestingly the posteromedial and posterolateral distances were less for the SEBT than the YBT. In contrast, the opposing skewness of the measured reach directions resulted in similar values for the calculated composite scores for the tests. In the literature, a cut-off score of greater than 4 cm absolute asymmetry in the anterior direction is often used to assess injury risk; however this value was established using a different population[47,286]. Within our adolescent female population, this cut-off score identified different subjects at-risk of injury depending on the test method. As a consequence, caution should be used when comparing the results from the SEBT and the YBT for a healthy physically active adolescent female population. When comparing these scores to the reported values for other populations within the literature, the test scores should remain exclusive to their specific population and test method[41,42,252].

The second portion of the thesis (Chapter 3) investigated whether there was a relationship between anthropometrics, lower limb variables and performance on the YBT in healthy and

ACL-injured adolescent females. Although the ACL-injured group was slightly older than the healthy group, anthropometric measurements were similar between groups, with the exception of measures for ACL laxity and the pedi-IKDC due to ACL injury. Participants were representative of a typical adolescent female population that participates in a variety of recreational sporting activities and is nearing or has recently reached physical maturation. The main findings were that YBT reach distances did not differ between healthy and ACL-injured subjects. However, the correlations among anthropometric and lower extremity variables differed between the healthy and ACL-injured. In healthy subjects, weight and BMI had a moderate inverse relationship with the YBT posterior reach distances, and lower extremity strength was positively correlated with PM and PL. Weak relationships were observed between knee-flexion ROM and the ANT and PL reach directions, and hip flexibility was correlated with the PM and PL reach directions. For the exploratory group of ACL-injured subjects, there was no relationship between the anthropometric characteristics and the YBT scoring. Hip flexibility had a moderate positive correlation with the ANT reach direction, and knee-flexion strength had a negative correlation with the PL reach direction. Results indicated that clinicians should emphasize improvements in these modifiable components (weight, BMI, hip flexibility and knee-flexion strength) in order to enhance YBT performance, and potentially decrease the risk of ACL injury for active adolescent females.

The third portion of the thesis (Chapter 4) was a kinematic assessment of the knee and ankle joint function during execution of the anterior reach direction of the YBT in healthy and ACL-injured adolescent females. Results suggested that there were no significant differences between the healthy and ACL-injured subjects on the YBT ANT reach direction scoring or lower extremity joint angles when performing the test. Data for healthy adolescents indicated that there

were relationships: YBT and ankle dorsiflexion and knee valgus, but not knee flexion. Results for the ACL-injured group suggested there were no relationships between ankle joint or knee joint angles and YBT ANT reach scoring. Interestingly, grouping subjects according to their performance on the YBT (above, within or below the 95% CI) failed to identify any consistencies between YBT scoring and lower extremity joint angles. A similar result was observed when single-subject analysis was performed. These findings reinforce the notion that adolescent females utilize a variety of joint movement strategies when performing the ANT reach direction of the YBT, and these results suggest that scoring on the YBT may offer clinicians limited insight into lower extremity joint kinematics when performing dynamic balance testing.

The final portion of the thesis (Chapter 5) investigated the safety and effectiveness of a perturbation-based neuromuscular exercise program on dynamic balance, lower limb proprioception, flexibility and strength in healthy and ACL-injured adolescent females. Results suggested that the perturbation training program was safe but had no statistically significant effect on YBT performance in either healthy or ACL-injured adolescent female participants. However, the number of healthy participants who attained clinically significant improvements in their YBT scoring was only significant for the PM reach direction after participants completed the perturbation training program (4 out of 12 participants, $p=0.05$). In healthy participants, hip abduction strength increased significantly following the perturbation training program, while all other measures of lower extremity strength were unaffected for both the healthy and ACL-injured participants. Knee proprioception and flexibility of the hip and ankle joints were unaffected by the training program. Results suggest participation in only a perturbation-based NME training is safe for healthy and ACL-injured adolescent females, however offers limited

benefits. Clinicians should consider using other outcome measures such as gait analysis or muscular reaction to an anterior tibial translation to evaluate the perturbation-based neuromuscular program. Additionally, while the 10 session training program (2 x 5 weeks) was effective for the ACL-injured physically active adult population, an increase in the training volume may be necessary to elicit changes for adolescents, and should be considered for future investigations targeting this critical population.

2. Impact of Research

Clinicians often use the SEBT and YBT to functionally screen athletes who are at-risk of injury, assess deficiencies following injury, and to monitor rehabilitation progress[35]. While either test is appropriate to assess dynamic balance in adolescent females, clinicians often inadvertently compare and interchange scoring and injury risk thresholds for this at-risk population with normative values established for different populations. Results of this research indicate that similar to the adult population, discussion of test scores should always be specified as exclusive to the specific population and test method[41,42,252]. Our data provide the literature with previously lacking reference values for clinical dynamic balance test scores for the recreationally, active healthy and ACL-injured adolescent female population.

Additionally, by investigating the influence of anthropometric characteristics and lower extremity variables on dynamic balance scoring, we identified modifiable components that clinicians can address during prevention and rehabilitation programs. In healthy adolescent females BMI and strength could be considered, while flexibility and strength in ACL-injured could be addressed as potential areas to improve dynamic balance, and reduce injury risk, as they influence YBT scoring.

As altered knee kinematics and deficits in postural stability have been linked to the potential cause of the increased incidence of ACL injuries in adolescent females[35,49,157–159,339], we further investigated the YBT to determine if lower limb movement strategies during the execution of the YBT would influence scoring. An individual's movement strategy can be assessed by evaluating three main aspects of the proprioception process; the afferent, central processing and efferent components. Threshold to detection of passive motion (TTDPM) and joint position sense (JPS) methods are often used to assess the afferent response of joint mechanoreceptors[106]. The central component of cortical processing and neuroplasticity have been investigated using emerging tests such as electroencephalography (EEG)[107], somatosensory evoked potentials (SEP)[108], functional MRI (fMRI)[109] and neurocognitive assessment tools (IMPACT)[110]. The efferent aspect of proprioception, or neuromuscular response, is most commonly assessed by kinematic evaluation or electromyographic (EMG) activity[106]. Our assessment of participant's movement strategies focussed on kinematic evaluation of the knee and ankle joint in a clinical setting. Interestingly, data suggested that both healthy and ACL-injured adolescent females utilized a wide range of movement strategies to achieve similar reach distances. However the relationship between kinematics and YBT scoring differed between healthy and ACL-injured, suggesting that ACL-injured adolescent females may utilize different strategies for movement at the hip or within the trunk to protect their injured knee. Thus clinicians should monitor the full-body movement during dynamic balance testing, in addition to recording the quantitative reach distance scores.

Given their high risk for ACL injury, safe and effective prevention and rehabilitation programs for recreationally active adolescent females are essential in modern practice. Our results suggest that injury-prevention and rehabilitation programs which utilize 'stand-alone' perturbation-based

NM training are safe, but offer limited benefit to healthy adolescent females, and no preoperative benefit to ACL-injured adolescent females. Clinicians should consider utilizing other main outcome measures to assess the effectiveness of perturbation-based NM training, as well as investigate the impact of increasing the training volume of the program with this at-risk population.

3. Limitations of the Research

It is important to acknowledge that our study did have several limitations. The first limitation was that we intentionally choose to investigate the specific population of recreationally active, adolescent female population. This limits the generalizability of our results to other populations, but addressed an important deficiency in the literature regarding clinical dynamic balance tests and perturbation-based NM training for this at-risk population.

A second limitation is that our *a priori* power analysis indicated that the sample size for healthy individuals of 24 was appropriate to assess our primary outcome measure, dynamic balance. An *a priori* analysis indicated that data for 22 subjects for both the healthy and ACL-injured groups would be required to adequately power the evaluation[48,289]. Unfortunately age, gender, and activity-level inclusion criteria limited our ACL-injured recruitment to only an exploratory group of 10 subjects. Additionally, we were unable to access the medical records for our ACL-injured subjects to record the presences of any concomitant injuries such as MCL strains, meniscal tears or chondral lesions. Future studies will need more subjects to establish normative values for ACL-injured, recreationally active adolescent females.

Another point to consider is that while protocols have been established for the clinical dynamic balance test, there are several methodological and procedural disparities reported within the literature. For the SEBT, the main variation is in the stance limb foot placement for the SEBT.

Some studies place the heel at the centre of the grid[35,289,289], or aligned the most distal aspect of the toes to the centre of the grid[41,42,46,47]. Others switched foot-stance positions for the anterior versus the posterior reach directions[258,374]. There were additional variations in whether the stance limb was barefoot[35,36,39,41–44,46,258,286,374] or shod[38,45,48,49] and if hand placement was required to stay on hips[36,39,41,42,46,258,289,374] or not specified[35,38,43–45,48,49,286].The exact impact that each of these subtle variations may have on reach direction is unknown, and was beyond the scope of our current investigation. They certainly warrant further investigation. For the YBT, the typical protocol in adults involves four training trials and three test trials to report a reach distance as the average of the three test trials[38]. Variations such as the average of the last 3 of 6 successful attempts[199], the best of 3 successful trails[200], or 1 practice and 2 test trials[201] have been reported. A recent study recommended that 6 practice trails and 3 test trials should be performed in an adolescent male population to increase the reliability of YBT assessments[373]. Further standardization of the SEBT and YBT protocols will allow for more accurate comparisons of test scoring between the test methods and studies.

The final major limitation for this research project was the inability to assess the posterior reach directions of the YBT in our kinematic assessment. We were restricted to an analysis of lower extremity movement during execution of only the anterior reach direction as more sophisticated 3D motion-capture equipment is required to capture the additional rotational movements associated with the posterolateral and posteromedial reach directions[42,366]. Beyond this, time restrictions in the data collection protocol employed for the present study limited videotaping during each subject's testing session to only one trial. Assessment of each of the three test trials throughout the full range of movement (rather than at the maximal reach position) may have

been a more accurate approach for identifying the interactions between joint positioning and scoring on the dynamic balance test.

4. Future Directions

As with many research projects, results often lead to new questions. Normative dynamic balance scores for a healthy and ACL-injured female adolescent population is limited in the literature. Future investigations that could assess a large sample sizes would provide valuable normative scores, establish appropriate injury threshold cut-off scores and offer a needed source of comparison for other studies. As the proprioceptive, vestibular, and visual systems that contribute to dynamic balance are still developing during maturation[154,295,297], a longitudinal assessment throughout adolescence would be able to assess the impact of each of these components during this critical time of developmental. Additionally, assessing male adolescents of a similar age, sport and competitive level might highlight sex-specific differences that contribute to the increase risk of ACL-injuries in females. Establishing a physical literacy and knee injury database in conjunction with the local high school board (Winnipeg High School Athletics Association) could allow for physical measurements and injury rates of a large number of male and female adolescents to be monitored over successive years. The methods of assessment for anthropometric characteristics (height, weight and BMI), dynamic balance (mSEBT and YBT), proprioception (WB-JPS), flexibility (standing toe-touch and weight-bearing lunge test), strength (HHD of the lower extremity) and lower limb kinematics (2D video analysis) incorporated in this current project are portable and could easily be conducted in regularly scheduled physical education or health and wellness class.

We choose methodologies that were easily accessible to sports medicine clinicians for evaluating proprioception, strength, flexibility and strength. Other techniques, that often require more sophisticated equipment, such as isokinetic dynamometry testing for strength and proprioception, EMG analysis for muscle activity, and 3D gait analysis for kinematic joint movement, are available and may provide a more comprehensive analysis of the components associated with dynamic balance. Thus, if we shifted from a clinically-based to a laboratory-based experimental design, Biodex dynamometry could be used to assess lower extremity proprioception (via the TTDPM methods) and isokinetic strength. This approach would allow documentation of detailed parameters (eg. peak torque, total work, angle of peak torque) of dynamic muscle strength, and facilitate direct comparison of strength data from our patients with previously published reports on dynamic strength. Inclusion of EMG analysis of the lower extremity musculature (gluteals, hamstrings, quadriceps and gastrocnemius) during completion of the YBT would allow for a more detailed assessment of the movement strategies utilized by participants. Additionally, using a 3D motion capture system would also support a kinematic analysis of the trunk, pelvis and lower extremity of all three reach directions of the YBT, which was unattainable with our current methodological design employed in our current investigation.

Finally, while the literature suggests that a neuromuscular training program for females athletes should include a combination of strength training, plyometrics, balance training with technique monitoring feedback[203], investigations such as ours that examine the isolated components of a neuromuscular program are necessary to determine the individual benefits of each type of training. Future investigations should consider evaluating the effectiveness of combining perturbation and other training methods for preventative and pre-operative rehabilitation in the at-risk adolescent female population. In partnership with a therapeutic rehabilitation clinic, we

could compare the safety and effectiveness of a "standard pre-habilitation program" which would typically incorporate range of motion, basic strength and cardiovascular exercises versus a "standard plus perturbation-based NM training program." It would be interesting to include both adult and adolescent participants to investigate if the maturation process influences the outcome measures.

5. Conclusion

The following are the key findings which address the specific aims and objectives of our examination of clinical dynamic balance tests and a perturbation-based NM exercise program in adolescent females. Our investigation of two commonly utilized clinical dynamic balance tests, the SEBT and YBT, in a healthy adolescent female population (Chapter 2) indicated that:

- Measured reach directions differ between the mSEBT and YBT in adolescent females.
- Calculated composite scores are similar for the mSEBT and YBT in adolescent females.
- Using the established injury risk cut-off score of greater than 4 cm absolute asymmetry in the anterior direction for the mSEBT and YBT identified different subjects at-risk of injury in adolescent females.
- Caution should be used when comparing the various outcome scores from the mSEBT and the YBT in adolescent females.

The study which examined whether there was a relationship between anthropometrics, lower limb variables and performance on the YBT in healthy and ACL-injured adolescent females (Chapter 3) concluded that:

- Although the ACL-injured group was slightly older than the healthy group and had increased ACL laxity, anthropometric measurements of height, weight and BMI were similar between groups.
- Lower extremity variables of proprioception and flexibility were similar between the groups, while healthy subjects had greater knee joint ROM and hip abduction strength than ACL-injured subjects.
- YBT reach distances did not differ between healthy and ACL-injured subjects.
- In healthy subjects, weight and BMI had moderate inverse correlations with the posterior reach directions of the YBT. Lower extremity strength was positively correlated with the PM and PL reach directions.
- The exploratory group of ACL-injured subjects showed no relationships between the anthropometric characteristics, lower extremity strength and the YBT.

Our kinematic assessment of the knee and ankle joint function during execution of the anterior reach direction of the YBT in healthy and ACL-injured adolescent females (Chapter 4) indicated that:

- There were no significant differences between the healthy and ACL-injured subjects on the YBT ANT reach direction scoring or lower extremity joint angles when performing the test.
- Healthy adolescents indicated a relationship between scoring on the YBT and the angle of ankle dorsiflexion and the angle of knee valgus, but no relationship with the angle of knee flexion. While ACL-injured subjects demonstrated no relationships between ankle or knee joint angles and YBT ANT reach scoring.

- Healthy and ACL-injured adolescent females utilize a variety of joint movement strategies when performing the ANT reach direction of the YBT.

Finally, an investigation of the safety and effectiveness of a perturbation-based neuromuscular exercise program on dynamic balance, lower limb proprioception, flexibility and strength in healthy and ACL-injured adolescent females (Chapter 5) concluded that:

- The perturbation-based NM training program was safe but had no statistically significant effect on YBT performance in either healthy or ACL-injured adolescent female participants.
- Clinically significant improvements in YBT performance by healthy participants were observed for the PM reach direction after participants completed the perturbation-based NM training program.
- Knee proprioception and flexibility of the hip and ankle joints were unaffected by the perturbation-based training program.
- In healthy participants, hip abduction strength increased significantly following the perturbation-based NM training program, while all other measures of lower extremity strength were unaffected for both the healthy and ACL-injured participants.

Given their high risk for ACL injury, safe and effective prevention and preoperative rehabilitation programs for recreationally active adolescent females are essential in clinical sports medicine practice. Various neuromuscular training programs have indicated beneficial results for injury prevention in this population, although many of the techniques currently used are not ideal for ACL-injured subjects. In previous studies involving both healthy and ACL-injured adult populations, perturbation-based NM training has been a safe and effective

intervention, but had yet to be evaluated in the adolescent female population. Results of the present research suggest that perturbation-based NM training is safe; however, as a stand-alone program it offers limited benefit to prevention for healthy adolescent females, and no preoperative benefit to ACL-injured adolescent females. While clinical dynamic balance tests can be used to evaluate adolescent females, clinicians are reminded that scoring is exclusive to the specific method utilized and demographics of the population being evaluated. To enhance YBT performance, and potentially decrease the risk of ACL injury, the modifiable components of BMI, and lower extremity flexibility and strength should be addressed. In addition to reach distance, movement strategies should be assessed during performance of clinical dynamic balance tests. While a wide range of movement strategies can be utilized to achieve similar reach distances during execution of the YBT, differences in lower extremity kinematics may indicate coping mechanisms due to injury and warrant further investigation. Thus, results of this research provide researchers and clinicians with information that should clarify the current literature and which could positively impact the current standard of care for the prevention and pre-operative management of ACL-injured adolescent females.

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Appendix A: Perturbation-based NM Training Program Protocol

Early Phase (Sessions 1-4)

Treatment Goals:

- Expose athlete to perturbations in all directions
- Elicit an appropriate muscular response to applied perturbations (no rigid co-contraction)
- Minimize verbal cues

Movement Application:

- ***Inform patient*** of direction & timing
- Slow force; Low magnitude
- Each set 1 min

Session	Rocker Board	Roller Board/Platform	Roller Board
1	• Bilateral stance • 2 sets anterior/posterior • 2 sets medial/lateral	• 2 sets with injured limb on roller board, anterior/posterior • 2 sets with uninjured limb on roller board, anterior/posterior • 2 sets with injured limb on roller board, medial/lateral • 2 sets with uninjured limb on roller board, medial/lateral	• Bilateral stance • 2 sets anterior/posterior • 2 sets medial/lateral
2	• Unilateral stance • 2 sets anterior/posterior • 2 sets medial/lateral	• 2 sets with injured limb on roller board, anterior/posterior • 2 sets with uninjured limb on roller board, anterior/posterior • 2 sets with injured limb on roller board, medial/lateral • 2 sets with uninjured limb on roller board, medial/lateral	• Unilateral stance • 2 sets anterior/posterior • 2 sets medial/lateral
3	• Unilateral stance • 3 sets anterior/posterior • 3 sets medial/lateral	• 3 sets with injured limb on roller board, anterior/posterior • 3 sets with uninjured limb on roller board, anterior/posterior • 3 sets with injured limb on roller board, medial/lateral • 3 sets with uninjured limb on roller board, medial/lateral	• Unilateral stance • 3 sets anterior/posterior • 3 sets medial/lateral
4	• Unilateral stance • 3 sets anterior/posterior • 3 sets medial/lateral	• 3 sets with injured limb on roller board, anterior/posterior • 3 sets with uninjured limb on roller board, anterior/posterior • 3 sets with injured limb on roller board, medial/lateral • 3 sets with uninjured limb on roller board, medial/lateral	• Unilateral stance • 3 sets anterior/posterior • 3 sets medial/lateral

Mid Phase (Sessions 5-7)

Treatment Goals:

- Add light sport-specific activity during perturbation techniques
- Improve athlete accuracy in matching muscle responses to perturbation intensity, direction and speed

Movement Application:

- ***Unexpected forces***
- ***Rapid, increasing magnitude*** force application
- ***Short delay*** between subsequent force applications
- Begin ***combining directional movement*** of roller board
- ***Distraction*** via ball toss (Beginning at sessions 6)

Session	Rocker Board	Roller Board/Platform	Roller Board
5	• Unilateral stance • 2 sets anterior/posterior • 2 sets medial/lateral	• 1 set with injured limb on roller board, anterior/posterior • 1 set with uninjured limb on roller board, anterior/posterior • 1 set with injured limb on roller board, medial/lateral • 1 set with uninjured limb on roller board, medial/lateral • 2 sets with injured limb on roller board, combination movement • 2 sets with uninjured limb on roller board, combination movement	• Unilateral stance • 1 set anterior/posterior • 1 set medial/lateral • 2 sets combination movements
6	• Unilateral stance • 2 sets anterior/posterior • 2 sets medial/lateral	• 1 set with injured limb on roller board, anterior/posterior • 1 set with uninjured limb on roller board, anterior/posterior • 1 set with injured limb on roller board, medial/lateral • 1 set with uninjured limb on roller board, medial/lateral • 2 sets with injured limb on roller board, combination movement • 2 sets with uninjured limb on roller board, combination movement	• Unilateral stance • 1 set anterior/posterior • 1 set medial/lateral • 2 sets combination movements
7	• Unilateral stance • 2 sets anterior/posterior • 2 sets medial/lateral	• 1 set with injured limb on roller board, anterior/posterior • 1 set with uninjured limb on roller board, anterior/posterior • 1 set with injured limb on roller board, medial/lateral • 1 set with uninjured limb on roller board, medial/lateral • 3 sets with injured limb on roller board, combination movement • 3 sets with uninjured limb on roller board, combination movement	• Unilateral stance • 1 set anterior/posterior • 1 set medial/lateral • 3 sets combination movements

Late Phase (Sessions 8-10)

Treatment Goals:

- Increase difficulty of perturbation by using sport-specific stances
- Obtain accurate, selective muscular responses to perturbations in any direction & any intensity, magnitude or speed

Movement Application:

- ***Increased magnitude*** force application
- ***Random direction*** movements
- ***Little to no delay*** between applications
- ***Distraction*** via ball toss

Session	Rocker Board	Roller Board/Platform	Roller Board
8	• Unilateral stance • 1 set random (linear foot) • 2 sets random (diagonal foot)	• 2 sets with injured limb on roller board, combination movement • 2 sets with uninjured limb on roller board, combination movement • 1 set with injured limb on roller board, combination movement (no delay) • 1 set with uninjured limb on roller board, combination movement (no delay)	• Unilateral stance • 2 sets combination movements • 1 set combination movements (no delay)
9	• Unilateral stance • 1 set random (linear foot) • 2 sets random (diagonal foot)	• 3 sets with injured limb on roller board, combination movement (no delay) • 3 sets with uninjured limb on roller board, combination movement (no delay)	• Unilateral stance • 3 sets combination movements (no delay)
10	• Unilateral stance • 1 set random (linear foot) • 2 sets random (diagonal foot)	• 3 sets with injured limb on roller board, combination movement (no delay) • 3 sets with uninjured limb on roller board, combination movement (no delay)	• Unilateral stance • 3 sets combination movements (no delay)

Appendix B: Participant Consent Form

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CONSENT TO PARTICIPATE IN RESEARCH STUDY

Title of Study: The Effectiveness of Neuromuscular Exercise (NME) Training in Healthy and ACL-injured Adolescent Females

Principal Investigator:

Dr. Jason Peeler PhD., CAT(C)
College of Medicine, Department of Human Anatomy & Cell Science, University of Manitoba, (204) 272-3146

Co-Investigators:

Dr. Jeff Leiter M.Sc., PhD.
Pan Am Clinic, 75 Poseidon Bay, Winnipeg, (204) 927-2665

Dr. Peter MacDonald MD, FRCS(C)
Pan Am Clinic, 75 Poseidon Bay, Winnipeg, (204) 925-7480

Date: February 15, 2015

Your child is being asked to participate in a clinical research study. Please take your time to review this consent form and discuss any questions you may have with the study staff. You may take your time to make your decision about participating in this study and you may discuss it with your friends, family or (if applicable) your doctor before you make your decision. This consent form may contain words that you do not understand. Please ask the study staff to explain any words or information that you do not clearly understand.

1. Purpose of the Study

This clinical trial is being conducted to determine the effect of an established neuromuscular training (NMT) program on the knee joint function in healthy and ACL-injured adolescent females. This investigation should provide researchers and clinicians with valuable information regarding the effectiveness of NMT in the skeletally immature as both a non-operative rehabilitation protocol to improve the management of ACL-injured patients awaiting surgical reconstruction, as well as a preventative method to decrease the occurrence of ACL injuries in healthy individuals.

2. Time Commitment

The total time commitment for your participation in the study (outside of your regularly scheduled doctors appointments) will be approximately of 13 hours. Each session will be approximately 1 hour in duration. Over 7 weeks, subjects will participate in 3 test sessions and 10 neuromuscular exercise training.

3. Procedures

For the investigation, approximately 22 healthy knee and 22 ACL-injured knee participants will be recruited. Subjects will self-report their stage of maturation via the pubertal maturation observation scale (PMOS) questionnaire. ACL-injured participants will be confirmed by a clinical evaluation. All participants will complete a standardized screening protocol to ensure they are physically fit for participation in the testing and exercise program. Participants will then be **randomly** assigned to into the NME training group or the no exercise group. Participants will complete 3 follow-up test sessions at the following time points: two sessions during week 1, and one session at week 7. The exercise protocol requires that the participant attends 2 supervised training sessions per week, over the 5 week period (for a total of 10 sessions). During each training session the patient maintains balance on three different support surfaces (rockerboard, rollerboard & platform), while a clinician administers purposeful manipulations. Each leg will receive training on each of the support surfaces. Upon completion of testing, the no exercise group will be given the option to complete the 5-week NME training program.

All testing will be administered by a Research Assistant under the supervision of the Study Coordinator. Training sessions will be with a Certified Athletic Therapist or Physiotherapist.

Participants will be asked to complete the following forms or procedures as part of the data collection for the assessment of knee function:

- Knee demographic & anthropometric form
- Pubertal Maturation Observational Scale (PMOS)
- KT-1000 arthrometer test
- Standardized Screening protocol
- Modified International Knee Documentation Committee (pedi-IKDC) form
- Physical Activity Questionnaire for older children (PAQ-C)
- Star Excursion Balance test
- Y-Balance test
- Hand-held Dynamometer testing
- Core Stability test
- Flexibility tests
- Proprioception test
- Functional Performance test

Participant's name and date of birth may be used to access patient charting and medical imaging (ie. x-rays or MRI) information contained at Pan Am Clinic in order to confirm the diagnosis of a torn anterior cruciate ligament.

4. Discomfort and Risk

Your child may feel slight discomfort and/or muscle soreness while performing the assessment of knee function and exercises, but this should be no more painful than what they experience during everyday activities such as playing. There is a risk of falling

during the exercise program and a small risk sustaining an injury to supporting knee structures, such as the meniscus.

5. Benefits

By participating in this study, your child will be providing information to the study researchers, clinicians and doctors that may allow them to better manage ACL injuries in the adolescent population. Beyond this, there may or may not be direct medical benefit to you from participating in this study.

You and your child are not waiving any of your legal rights by signing this consent form nor releasing the investigator(s) or the sponsor(s) from their legal and professional responsibilities.

6. Compensation

You are participating in this study on a volunteer basis, and all clinic and professional fees, diagnostic and laboratory tests that will be performed as part of this study are provided at no cost to you. There will be no cost for the study assessment that you will receive. At the completion of the study your child will receive an honourarium of a $50 gift card, the equivalent of $5.00 for every training session attended, to cover any travel, parking or meal expenses occurred during participation in the study.

7. Confidentiality

Information gathered in this research study may be published or presented in public forums; however your name and other identifying information will not be used or revealed. Medical records that contain your identity will be treated as confidential in accordance with the Personal Health Information Act of Manitoba. Despite efforts to keep your personal information confidential, absolute confidentiality cannot be guaranteed. Your personal information may be disclosed if required by law. All study documents related to you will bear only your assigned patient number (or code) and /or initials.

*The University of Manitoba **Health** Research Ethics Board may review research-related records for quality assurance purposes.*

All records will be kept in a locked secure area and only those persons identified will have access to these records. If any of your medical/research records need to be copied for any of the above, your name and all identifying information will be removed. No information revealing any personal information such as your name, address or telephone number will leave the Pan Am Clinic.

8. Voluntary Participation/Withdrawal from the Study

Your child's decision to take part in this study is voluntary. Your child may refuse to participate or withdraw from the study at any time. However, we would like to encourage you and/or your child to talk to the study supervisor and/or staff, prior to making such a decision. Your decision not to participate or to withdraw from the study will not affect your care at this centre.

If the study staff feels that it is in your child's best interest to withdraw you from the study, they will remove you without your consent.

We will tell you about any new information that may affect your health, welfare, or willingness to stay in this study.

9. Medical Care for Injury Related to the Study

In the case of injury or illness resulting from this study, necessary medical treatment will be available at no additional cost to you. If you should become physically injured as a result of any research activity, the study doctor will provide any necessary treatment, at no charge, to help you promptly recover from the injury.

You and your child are not waiving any of your legal rights by signing this consent form nor releasing the investigator(s) their legal and professional responsibilities.

10. Questions

You and your child are free to ask any questions that you may have about your treatment and your rights as a research participant. If any questions come up during or after the study or if you have a research-related injury, contact the Principle Investigator: Dr. Jason Peeler at (204) 272-3146 and/or the Study Coordinator: Alison Longo at (204) 927-2829. For questions about your rights as a research participant, you may contact The University of Manitoba, Bannatyne Campus Research Ethics Board Office at (204) 789-3389

Do not sign this consent form unless you have had a chance to ask questions and have received satisfactory answers to all of your questions.

11. Results of the Study

All individuals who participate in this study are eligible to receive information on the outcomes of the study, via a 1 page synopsis of the key findings of the research. If you would like to receive information on the results of this study please state your mailing address below:

Address: _____

City: _____

Postal code: _____

Email: _____

Statement of Consent:

I have read this consent form. I have had the opportunity to discuss this research study with Dr. Jason Peeler or his study staff. I have had my questions answered by them in language I understand. The risks and benefits have been explained to me. I believe that I have not been unduly influenced by any study team member to participate in the research study by any statements or implied statements. Any relationship (such as employer, supervisor or family member) I may have with the study team has not affected my decision to participate. I understand that I will be given a copy of this consent form after signing it. I understand that my child's participation in this study is voluntary and that I may choose to withdraw them at any time. I freely agree to allow my child to participate in this research study.

I understand that information regarding my child's personal identity will be kept confidential, but that confidentiality is not guaranteed. I authorize the inspection of any of my child's records that relate to this study by The University of Manitoba Research Ethics Board for quality assurance purposes.

By signing this consent form, I have not waived any of the legal rights that I (or my child) have as a participant in a research study.

I give permission to be contacted for future research in relation to this study.
☐Yes ☐ No

Parent/Legal Guardian's printed name: _____

Parent/Legal Guardian's signature: _____

Child's printed name: _____

Child's signature: _____

Date: _____
(day/month/year)

I, the undersigned, have fully explained the relevant details of this research study to the participant named above and believe that the participant has understood and has knowingly given their consent

Printed Name: _____ Date _____
(day/month/year)

Signature: _____

Role in the study: _____

Relationship to study team members:_____

Appendix C: Assent Form for Children Under 15 Years of Age



UNIVERSITY OF MANITOBA



RESEARCH PARTICIPANT INFORMATION AND CONSENT FORM
(ASSENT FORM FOR CHILDREN UNDER 15 YEARS OF AGE)

Title of Study:
The Effectiveness of Neuromuscular Exercise (NME) Training in Healthy and ACL-injured Adolescent Females.

Principal Investigator:
Dr. Jason Peeler, University of Manitoba

Co-Investigators:
Dr. Jeff Leiter & Dr. Peter MacDonald, Pan Am Clinic

Why you are here?
The researchers want to tell you about a study about exercises to help children prevent knee injuries and help children if they hurt their knee. They want to see if you would like to be in this study. This form tells you about the study. If there is anything you do not understand, please ask your parents/guardian or the study staff.

Why are they doing this study?
The researchers want to see if the exercises can improve how the knee works in children with healthy knees and in children who have injured their knee.

What will happen to you?
If you want to be in the study these things will happen:

1. The researcher's may use your name and date of birth to access your medical charting and medical imaging (ie. x-rays) information contained at Pan Am Clinic in order to confirm that you have been diagnosed with a torn anterior cruciate ligament.
2. The study will last 7 weeks, but you don't have to come in every day. You will be asked to come to the Pan Am Clinic for 3 visits to perform activities to test your knee, and for 10 visits to perform exercises for your knee.
3. The 3 test visits for your knee will be twice at the beginning, and once at the end of the study. Each test visit last about 1 hour. The researchers will ask you questions about how your knee feels and what activities you are able to do. They will ask you to perform some simple activities to test your knee, for example activities to see how strong it is and how well you can balance on one leg.
4. You will be **randomly** assigned to either the NME training group or no exercise group. However, at the end of the study the no exercise group will be given the option to complete the training program.

5. The 10 exercise visits will be 2 visits per week for 5 weeks. Each exercise visit will last about 1 hour. A therapist will work with you to perform exercises for your knee, like balancing on a surface that moves.

Will the study hurt?
The movements that you will be asked to do are ones that you do every day when walking or playing, and should not hurt at all. If for some reason the movements hurt, you can stop right away.

Will you get better if you are in the study?
If you have an injured knee, this study won't fix it. But the researchers might find out something that will help other children like you in the future.

What if you have any questions?
You (or your mom or dad) can ask questions any time, now or later. You should feel free to talk to the researchers, your family or someone else about this study at anytime.

Who will know what I did in the study?
Any information you give to the study staff will be kept private (*or secret*). Your name will not be on any study paper and no one but the study staff and the researcher will know that it was you who was in the study.

Do you have to be in the study?
You do not have to be in the study. No one will be mad at you if you don't want to do this.
Participating in the study is on a volunteer basis. At the end of the study you will get compensation of $50 gift card (equal to $5.00 for every training visit you complete).
If you don't want to be in this study, just say so. We will also ask your parents if they would like you to be in the study. Even if your parents want you to be in the study you can still say no.
Even if you say yes now you can change your mind later. It's up to you.
Do you have any questions?

Assent

I want to take part in this study. I know I can change my mind at any time.

Child's printed name: _____ Verbal assent given Yes ☐

Child's signature: _____ Age: _____

Date: _____ (day/month/year)

I confirm that I have explained the study to the participant to the extent compatible with the participants understanding, and that the participant has agreed to be in the study.

Printed name of person obtaining assent: _____

Signature of person obtaining assent: _____

Date: _____ (day/month/year)