THE RELATIONSHIP BETWEEN TWO TASKS OF DYNAMIC POSTURAL STABILITY

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Postural stability assessments are commonly utilized in evaluating the risk of injury, measuring neuromuscular deficiencies, and quantifying improvement after intervention. Postural stability can be measured using static or dynamic tasks. Previous research has demonstrated that there is no relationship between measures of static and dynamic postural stability, proposing the theory that dynamic tasks may be more challenging in neuromuscular control. Different measures of dynamic postural stability may also vary in difficulty and their relationship should be examined.[7, 41, 51, 56] The Star Excursion Balance Test (SEBT) and Dynamic Postural Stability Index (DPSI) are both assessments intended to measure dynamic postural stability, but due to methodological differences each may challenge the sensorimotor system differently.[21, 32, 72] Dynamic measures should also be compared to a static task to determine if one is more strongly correlated to a Single Leg Balance Test (SLBT). It was hypothesized that the relationship between the SEBT measures and DPSI composite scores would not be significant. Additionally, it was hypothesized that the SLBT and SEBT measures would demonstrate a significantly stronger relationship than the relationship between the SLBT and DPSI composite scores.

Twenty-one healthy, active participants volunteered to participate in this study. Each participant performed postural stability testing including the SLBT, SEBT and DPSI jump task. A correlation coefficient was calculated between SEBT measurements and DPSI composite

scores. The relationship was not significant (r = 0.145, p = 0.554), indicating that scores from the two different dynamic tasks are not comparable and are potentially measuring different components of the sensorimotor system. The relationship between the SLBT and SEBT (r = 0.339, p = 0.156) was not significantly different from the relationship between the SLBT and DPSI (r = -0.035, p = 0.887; t = 1.443, p = 0.168). While postural stability assessments may not differ in difficulty, these findings help support the theory that different types of postural stability assessments are measuring different aspects of postural control. The outcomes from this study should validate the comprehensive use of multiple, differing postural stability tasks when measuring postural stability, and also when using tasks as a part of neuromuscular training.

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PREFACE

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1.0 INTRODUCTION

Postural stability assessments are commonly utilized in evaluating the risk of injury, measuring deficiencies in motor control resulting from injury, and quantifying improvement after injury intervention. Postural stability can be measured using a variety of static or dynamic tasks. Two examples of dynamic postural stability assessments are the Star Excursion Balance Test (SEBT) and Dynamic Postural Stability Index (DPSI).[17, 45, 72] The goal of the SEBT is to establish a base of support (BOS) before a disruption of postural stability is applied through reaching, while the DPSI testing procedures require the participant to perform a jump task and immediately establish a BOS and maintain postural stability upon landing.[32, 56, 72] Previous research has demonstrated that there is no relationship between measures of static postural stability and dynamic postural stability proposing the theory that dynamic tasks may be more challenging on the sensorimotor system.[7, 41, 51, 56] Measures of dynamic postural stability also vary in difficulty as well and should also be further examined. While the SEBT and DPSI are both measures of dynamic postural control, the tasks involved with each assessment appear greatly different and may challenge the neuromuscular control system differently as well.

The SEBT and DPSI have been found to be reliable and valid, but there is a lack of evidence to indicate the utilization of one test over the other despite methodological differences. One task may be more valid in measuring one construct or strategy of dynamic postural stability compared to another. It could also be argued that perhaps postural stability is more of a continuum ranging from more static tasks to more dynamic tasks, rather than the classification into static versus dynamic. There is a need to examine the relationship between different measures of dynamic postural stability to determine if these tasks are in fact measuring the same variable.

1.1 POSTURAL STABILITY DEFINED

Postural stability can be defined as the process of coordinating corrective movement strategies and movement at the selected joints to remain in postural equilibrium.[49] Furthermore, postural equilibrium is the balanced state of forces and moments acting on the body's center of mass.[48] Maintaining postural equilibrium is accomplished through the acquisition of afferent information, integration of sensorimotor information by the central nervous system for the selection and coordination of motor responses, and finally the execution of appropriate and specific musculoskeletal movements.[48, 49] Researchers have utilized many different measures of postural stability to identify risk factors for injury and predictors of optimal performance.[2, 21, 28, 38, 45, 55, 59, 71, 76] Postural stability assessments are also commonly used in the clinical setting as rehabilitation tools for balance training and to quantify improvements and outcomes after injury or intervention.[21, 32, 38, 56, 76]

Postural stability can be classified as static or dynamic. Static postural stability is the maintenance of postural equilibrium on an unmoving BOS.[48] Dynamic postural stability has been defined as the ability to transfer the vertical projection of the center of gravity around the supporting base.[14] Kinzey et al.[32] further described dynamic activities as those that cause the center of gravity to move in response to muscular activity arising from either an external or internal disturbance.[32] Dynamic postural stability has been measured by altering the surface of the supporting base or by altering the center of gravity by having the individual move.[56, 72] This description of dynamic postural stability is fitting for both the SEBT and DPSI, as both tasks require the individual to move and thus, alter the center of gravity. However, while the SEBT requires the maintenance of postural control during a slow, controlled reach, DPSI requires the establishment and maintenance of postural control following a single leg jump task.[32, 72] The tasks seem vastly different in the challenges imposed on the sensorimotor system. Tasks of static and dynamic stability have been shown to also challenge different components of the sensorimotor system.[7, 41, 51, 56] There is evidence to demonstrate the lack of a relationship between static and dynamic tasks that support the theory that maintaining static versus dynamic postural stability require different sensorimotor organs. .[7, 41, 51, 56] Similarly, a lack of correlation between performance on the SEBT and DPSI could indicate that two different tasks of dynamic postural control also require different sensorimotor strategies. Additionally, if one task is more closely related to a static postural stability task compared to the other, the results of this study could suggest that tasks of postural stability should not be classified as either static or dynamic, but perhaps fall on a continuum of postural control.

1.2 MEASUREMENTS OF POSTURAL STABILITY

1.2.1 Static Postural Stability Assessments

Static postural stability can best be defined as maintaining steadiness on a fixed, firm, unmoving base of support.[47] Furthermore, steadiness is defined as the ability to keep the body as motionless as possible.[14] Postural stability has been measured utilizing static postural stability tasks for decades.[12, 13] Static postural stability tasks can be categorized as double legged or single legged with eyes open while performing the task or eyes closed. While double leg stance assessments are useful, single leg postural stability assessments appear more appropriate for the healthy, athletic population.[47] During sports and physical activity an athlete is required to quickly stabilize on one foot and rely on the postural control system to maintain equilibrium on a very narrow BOS, rendering a single leg assessment more applicable to such a population. In addition, single leg assessments are also helpful because they allow researchers and clinicians to compare postural control bilaterally.[51]

A Single Leg Balance Test (SLBT) requires a participant to balance on one leg and maintain that position for a given amount of time. While there is argument over the best way to reduce and analyze data, it is agreed that force plate measures are the gold standard of assessment.[14, 38] A systematic review reported several different variables of static postural stability including center of gravity (COG), center of pressure (COP) and sway variability.[38] The COP measure represents the point of application of the resultant force in the horizontal plane. Previous research has demonstrated that there is a lack of correlation between COP and force variability measures, finding that force variability measures were more sensitive in detecting the differences between different static tasks and a stronger predictor of postural steadiness.[14, 15] The lack of correlation may also suggest that the two variables are measuring different components of overall postural control. Unlike sway variability and COP measures, COG measures cannot be calculated directly from GRF data but must be estimated based on anthropometric measurements.[61] Studies utilizing COG measures have found that postural stability is not a risk factor for lateral ankle sprain; however, this could be due to the lack of sensitivity of the measurement.[5, 74]

There are several studies to demonstrate the lack of correlation between static and dynamic tasks.[7, 41, 51, 56] However, there is significantly less research investigating the relationship between two different dynamic tasks, or comparing two different dynamic tasks to the same static task.[51] Similar to the lack of correlation between force and COP variability measures, these results of this study may indicate that static and dynamic measures of postural control are challenging different components of the sensorimotor system. The lack of relationships between different variables and tasks of postural stability should support the theory that postural stability is extremely multifaceted and may require a number of different measurements to examine postural stability, especially as a potential risk factor for injury.

1.2.2 Dynamic Postural Stability Assessments

It has been argued that static postural stability tasks may not be appropriate for testing deficiencies in the postural control of a healthy, athletic population.[51, 56] Through physical and sport specific training, high level athletes have developed adaptations to the sensorimotor system which allow these athletes to perform quick, agile moves such as cutting or pivoting with high proficiency. Therefore, testing should be difficult enough to challenge an individual with an enhanced sensorimotor system, most likely greater than that accomplished through a static postural stability task. There are several methods of testing dynamic postural stability which could be further categorized as BOS tasks, including the Star Excursion Balance Test (SEBT) and Y-balance test, and jump tasks, including the Time to Stabilization (TTS), Single Leg Hop Test, and Dynamic Postural Stability Index (DPSI).[32, 44, 47, 54, 72] The jump tasks all require the participant to take part in some sort of jump task or hop pattern and are assessed on how well or how quickly the subject can establish a BOS.[47, 54, 72] The BOS tasks are also considered dynamic; however, the BOS remains constant throughout the entire test.[32, 44]

1.2.2.1 Star Excursion Balance Test The Star Excursion Balance Test (SEBT) is widely accepted as an assessment of motor control and dynamic postural stability in both the clinic and laboratory settings. The goal of the test is for an individual to establish a stable BOS on the stance limb, and maintain that BOS through a series of slow, preplanned movements, maximally reach in one of eight prescribed directions: anterior, posterior, medial, lateral, anteromedial, anterolateral, posteromedial and posterolateral.[21] This task consists of a series of single-leg squats using the non-stance leg, and requires the combination of sagittal, frontal and transverse joint movements to maintain postural equilibrium through the reach.[17] The goal of the task is to reach as far as possible in order to maximally disturb the established BOS.[32] A greater maximal reach distance (MRD) indicates increased dynamic postural control.[21, 32]

The SEBT was originally developed as a rehabilitation tool. The SEBT has been found to be a valid and reliable measure in discriminating between groups and measuring improvements in motor control after injury or rehabilitation.[21] However, it is important to recognize that dynamic postural stability could potentially be more extensively measured using several different assessments. It could be argued that the SEBT is more similar to a static postural stability task compared to other dynamic postural stability tasks, because the BOS remains still or static during the SEBT. Perhaps these two different types of dynamic tasks place demands on different components of the sensorimotor system and if used concurrently, could provide more information than one test alone. It is still important to consider the extensive research that supports the efficacy of the SEBT in detecting differences in postural control in different populations and following injury, and support the continued utilization of the SEBT for these purposes. Therefore, there is a need to examine the relationship between the SEBT and a more dynamic, more functional task, such as DPSI, in order to determine if different measures of dynamic postural stability place similar challenges on the sensorimotor system, and if researchers can more comprehensively examine dynamic postural stability

1.2.2.2 Dynamic Postural Stability Index The Dynamic Postural Stability Index (DPSI) is a measure ”based on previous assessments of single-leg stance and single-leg hop stabilization tests with the underlying premise that dynamic postural stability depends on lower extremity kinematics at landing as well as on muscular activation patterns and eccentric control”.[53, 72] DPSI is a unitless measurement of dynamic postural stability based on GRF data. DPSI testing requires the individual to perform a jump task and land on a force plate, establish a BOS as quickly as possible, and maintain postural stability. Stability indices in the anterior-posterior, medial-lateral and vertical directions are calculated from the force plate data. The DPSI composite score provides researchers with a comprehensive measurement that considers changes in postural stability in all directions.[72]

1.3 POSTURAL STABILITY AS A RISK FACTOR FOR INJURY

While there is an abundance of research validating the use of postural stability measures to discriminate between injured and uninjured populations, the amount of studies utilizing postural stability assessments as a prospective risk factor for injury is more limited. Furthermore, a large amount of these prospective studies are focused on static postural control and the prediction of ankle injuries.[5, 36, 38, 64, 65, 67, 73, 74] A systematic review by McKeon et al[38] in 2008 reported some disagreement in results when using static postural stability measures to predict lateral ankle sprain.[38] Two of the reported studies examined postural stability using COP excursion measures as the sole predictor of lateral ankle sprain and found diminished static postural stability as a risk of ankle injury.[36, 65] However, other studies included in the review examined postural stability using COG excursion measurements, along with other risk factors as predictors of lateral ankle sprain and found that diminished static postural stability was not predictive of injury.[5, 73, 74] In addition, a more recent systematic review concluded that diminished postural control indicates increased risk of ankle injury in a healthy population and cited several prospective studies using different means for measuring static postural control.[10, 25, 27, 37, 76] Several studies have suggested that the potential reason for the discrepancy in findings could be due to the fact that static tasks are too simple and do not appropriately or accurately replicate the sport-specific movements typically associated with non-contact injury.[53, 56]

Measures of dynamic postural stability may be more suitable for measuring postural control in a healthy, athletic population; however, there is significantly less research utilizing measures of dynamic postural control as a predictor of lower extremity injury. One study used the SEBT to measure dynamic postural stability as a potential risk factor for injury in high school basketball players, and found that diminished postural control was predictive of lower extremity injury, including both ankle and knee sprain.[45] Two other studies used force plate balance systems with some sort of dynamic component (either rotating or tilting) to measure a balance index score or degrees of deflection, respectively.[43, 66] The first of these studies found that poor balance may be predictive of ACL rupture, while the second study found that poor dynamic postural stability is predictive of second ACL injury following reconstruction. [43, 66] While there is an abundance of research that uses static balance as a risk factor for injury, there is significantly less research that uses dynamic postural stability measures. In addition, there are no studies that use a jump task, such as DPSI, to measure dynamic postural stability as a risk factor for injury. The reason for the lack of research in this area may be because there are so many different types of dynamic postural stability assessments, and there is no general consensus about which dynamic assessment should be considered the “gold standard.” Therefore, it seems valuable to examine the relationship between these two measures to determine if the SEBT and DPSI are in fact challenging the same components of postural control, and they do not, is one of these tasks a more comprehensive measure of dynamic postural stability.

1.4 DEFINITION OF THE PROBLEM

Research has found separate measurements of postural stability to be reliable and accurate when discriminating between populations, determining the potential risk of injury, and measuring improvement after injury intervention. However, there is an array of different types of postural stability assessments, all seeming to place unique demands on the sensorimotor system. Previous research has demonstrated the lack of correlation between static measures of postural stability and both the SEBT and DPSI jump tasks. It could be argued that measures of dynamic postural control fall on a continuum of static to dynamic tasks, with certain assessments being more appropriate for specific research or clinical goals than others. It is therefore necessary to examine the relationship between different measures of dynamic postural stability in order to determine if different dynamic postural stability assessment tasks are challenging different constructs of the sensorimotor system. If the results of this study demonstrate a lack of correlation between the

SEBT and DPSI, it could be argued that the two assessments are actually measuring different postural stability strategies, and perhaps more than one dynamic postural stability assessment should be utilized when studying risk factors for injury.

1.5 PURPOSE OF THE STUDY

The purpose of this study is to examine the relationship between postural stability scores as measured by the SEBT and DPSI composite scores in order to determine if different dynamic postural stability assessments place different demands on the sensorimotor system. A secondary aim of this study is to examine the relationships between the SLBT and SEBT performance as well as the relationship between the SLBT and DPSI composite score in order to determine if one dynamic postural stability measurement is more correlated to static postural stability than the other.

1.6 SPECIFIC AIMS AND HYPOTHESIS

Specific Aim 1: To determine the relationship between SEBT normalized, average, composite maximum reach distance (MRD) and dynamic postural stability index (DPSI) composite score.

Hypothesis 1: There will be no significant relationship between the SEBT normalized, average, composite MRD and the DPSI composite score.

Specific Aim 2: To compare the linear relationships between the SLBT score and dynamic postural stability measurements using the SEBT and DPSI.

Hypothesis 2: Dynamic postural stability measuring using the SEBT will have a significantly stronger relationship with the SLBT compared to dynamic postural stability measured using DPSI.

1.7 STUDY SIGNIFICANCE

There are many ways to measure postural control, both static and dynamic. While there is research to demonstrate that there is no relationship between measures of static and dynamic postural control, there is no study examining the relationship between different measures of dynamic postural stability. If there is no relationship found between the SEBT measurements and DPSI scores, results would demonstrate that not all measures of dynamic postural stability are equal challenges of neuromuscular control. Furthermore, if these two measures of postural stability are not found to be correlated, it raises the question of which measurement of dynamic postural stability is best or more suited for different needs. The secondary aim of this study will demonstrate which dynamic measure is more related to static postural stability and may help to determine if one is more challenging than the other. These results would help researchers to have a better understanding of the relationship between different types of postural stability tasks. In addition, results could help to determine which measure is most appropriate in determining risk factor for injury, particularly in a healthy, athletic population. This study is performed in the hopes that further research can validate a "gold standard" of postural control.

2.0 REVIEW OF LITERATURE

The Review of Literature will provide an overview of previously published literature related to the current study. The first section will provide an overview of injury epidemiology and incidence of lower extremity injury related to postural stability. The second section will discuss how postural stability has been revealed as a potential prospective risk factor for injury. The third section will describe the components of the sensorimotor system and examine their individual roles in maintaining postural equilibrium during both static and dynamic tasks. This review will also include previous studies that have examined the relationships between assessments of static and dynamic postural stability in order to develop a better understanding for the significance of the current study. Finally, the methodology for this study will be considered thoroughly.

2.1 LOWER EXTREMITY INJURY EPIDEMIOLOGY

Injury prevention has long been a focus of sports medicine research. Several studies have found that diminished postural stability, both static and dynamic, as a risk factor for lower extremity injury.[36, 43, 45, 64-67] Injuries to the ankle and knee can be debilitating not only to the elite or collegiate athlete, but to the tactical and recreational athletic populations as well. More than 50% of injuries to reported by the National Collegiate Athletic Association (NCAA) Injury

Surveillance System (ISS) were to the ankle or knee, with ankle sprains accounting for about 15-28% of all injuries of the sample population.[26] Similarly, A recent epidemiological study found that 19.5% of surveyed troops serving in the United States Military sustained at least one nonbattle injury, with 38.8% of those troops sustaining multiple nonbattle injuries.[62] Sports/athletics were found to be the leading cause for self-reported “severe” nonbattle injuries at 22.3%.[62] The leading location of all hospitalized injuries in the US military was to the lower extremity, including the hip, upper leg, thigh, knee, lower leg, ankle, foot and toes.[31] Injuries to the lower extremity are not exclusive to elite collegiate athletes or the military, but occur in a frequent rate in the recreational athlete population as well.[8] While the rate of injury is alarming, perhaps more concerning is the amount of potential time out of sport or off of work resulting from an injury to the lower extremity. One in five ankle ligament injuries to collegiate athletes resulted in at least ten days off from training and sport.[26] Furthermore, 88% of injuries to the ACL also resulted in at least ten days off from training and sport, with the subsequent surgery taking anywhere from six months to a year off from training.[26] When considering the competitive nature of collegiate athletes, ten days is a significant amount of time to take off of training completely. In 2005, lower extremity sprains and strains in the military led to more than 1,800,000 days of limited duty among the Department of Defense (DoD) and four major branches of the armed forces.[31]

Even after recovery, there are potential long-term effects from these common, lower extremity injuries. Early onset osteoarthritis, pain, functional limitations and decreased quality of life have been associated with individuals who have previously suffered ACL or meniscus injuries.[35] A cohort study examined the long term effects of ACL injury in former female soccer players. Of 103 female subjects, eighty-four answered the Knee Injury and Osteoarthritis

Outcome (KOOS) questionnaire and sixty-seven consented to diagnostic imaging. The mean age of female participants was 31, approximately 12 years after injury. Of those who were imaged, 51% found early onset osteoarthritis and 63% reported symptoms affecting quality of life from the KOOS questionnaire.[35] In a companion study, 205 former male soccer athletes were investigated. The mean age of male participant was 34, approximately 14 years after injury. Of 205 participants, 122 agreed to radiographic imaging. Of these 122 male participants, nearly 80% demonstrated some radiographic changes in the knee, while 40% were diagnosed with OA.[35] Individuals who suffer from ankle injury may also experience long term effects. Anandacoomarasamy et al[1] examined individuals after sustaining a Grade 1 or 2 lateral ankle sprain, and found that 74% of those participants were still experiencing at least one symptom on the Short Form 36 scale, including symptoms of pain, feeling of giving way and swelling.[1] A common condition that recurs after sustaining an ankle sprain is functional ankle instability (FAI).[23, 70] One study utilized T2-mapping to examine functionally unstable ankles and found that unstable ankles demonstrated cartilage abnormalities in the majority of the joint.[16]

Based on the prevalence of lower extremity injury in active populations and the potential long-term and fiscal effects resulting from these injuries, it is necessary to identify modifiable neuromuscular characteristics as potential risk factors for injury.

2.2 POSTURAL STABILITY AS A RISK FACTOR FOR INJURY

It is clear that lower extremity injury can occur in many of the active population, and that the possible long-term consequences of these injuries can be extremely detrimental. Efforts have long been directed towards identifying risk factors for such injuries. Previous research has demonstrated diminished postural stability as a potential risk factor for lower extremity injury.[21, 38, 43, 45, 64-67, 76] While there is some disagreement amongst the results of studies using static postural stability assessments, those studies using dynamic postural stability tasks have demonstrated more consistent results.[5, 21, 43, 45, 66, 73, 74]

2.2.1 Static Postural Stability as a Risk Factor for Injury

One study investigating static postural stability as a potential risk factor for injury used stabilometry force plate measures to assess functional instability in a population of soccer players.[65] The primary variable was postural sway and was calculated using Center of Pressure (COP) measures. [65] The results of this study reported that of the twenty-nine individuals that demonstrated pathological stabilometry measures, twelve sustained ankle injuries in the following season (41%).[65] A pathological stabilometry value was defined as one that exceeded the mean value of the reference group by at least two standard deviations (SD); practically, a pathological value would indicate increased postural sway, and the inability of an individual to maintain postural equilibrium.[65] Of the ninety-eight individuals demonstrating normal stabilometry values, only eleven sustained ankle injury in the following season (11%), a significant difference from the pathological group ($p < 0.001$).[65] These findings suggest that the individuals with decreased stability are at greater risk of sustaining ankle injury, and may support the opinion that postural stability is a risk factor for injury.

Similarly, McGuine et al[36] found that individuals with diminished static postural stability were at increased risk for sustaining ankle injuries during the season.[36] This study examined 210 high school basketball players over the course of a sports season.[36] At the completion of the season, twenty-three subjects (10.9%) had sustained ankle sprains.[36] There was a significant difference between composite sway scores of injured and uninjured groups ($p = 0.001$).[36] In addition, there was an uneven distribution of ankle sprains when grouped by stabilometry scores. The seventy subjects with the highest sway scores demonstrated the highest rate of ankle sprain of 2.68/1000 exposures.[36] The seventy subjects with the middle group of sway scores had a decreased rate of ankle sprain (1.63/1000 exposures), while the seventy subjects with the lowest sway scores had the lowest rate of ankle injury of 0.40/1000 exposures ($p < 0.0002$).[36] Wang et al[67] found similar results when examining static postural stability as a potential risk factor for injury. Forty-two high school basketball players were assessed using postural sway measurements in the AP and ML axes and analyzed as separate variables.[67] After a season lasting approximately forty-six weeks, eighteen of the forty-two subjects (42.9%) sustained mild to moderate ankle sprains.[67] This study reported a significant difference between the magnitude of variation of ML postural sway values between the injured and non-injured groups ($p < 0.001$), and furthermore, described that those players with increased variation of postural sway in both axes were more likely to sustain an ankle injury ($p = 0.01$).[67] The results of these studies suggest that the athletes that demonstrate diminished static postural control are more likely to sustain an ankle sprain during their respective sport season.

A more recent study investigated static postural stability as a potential risk factor for injury, but rather than assessing postural sway with force plates, researchers measured a single leg stance clinically and categorized assessments as pass or fail.[64] A total of 230 high school and collegiate athletes were evaluated using the SLBT.[64] Tests were counted as failed/positive if the subject lost their balance or described a sense of imbalance.[64] These athletes were followed over the course of the fall season (approximately fourteen weeks) and reported any ankle injury disrupting the structures of the joint.[64] Of the total 230 athletes, twenty-eight sustained ankle injury during their sport season.[64] Nineteen of those individuals also demonstrated a positive SLBT demonstrating a significant association between a failed SLBT and sustaining an ankle sprain.[64] In this study, postural stability as measured by a clinical SLBT, was also predictive of ankle sprains in the following sport season.

The results of these studies should support the theory that individuals with diminished static postural stability are at increased risk of sustaining a lower extremity injury. However, it is important to note that other studies assessing static postural stability as a predictor of injury have found contradictory results. Beynnon et al[5] performed a comprehensive prospective study investigating several potential risk factors for injury including joint laxity, foot and ankle anatomy, isokinetic strength, AP COG measures, and muscle activation reaction time.[5] Risk factors were evaluated for 118 Division I men and women collegiate field athletes and followed over the course of a season.[5] The findings of this study reported no significant difference in postural stability, measured as COG angle, between the total athletes that sustained ankle ligament injury and those that remained healthy.[5] Another study examined multiple potential risk factors for ankle injury in male and female participants that major in health and physical activity.[73, 74] A total of 241 male participants and 159 female participants were tested for anthropometric characteristics, joint position sense, muscle strength, lower leg alignment, postural control and muscle reaction time.[73, 74] Postural control was assessed using the Neurocom Balance Master system. The primary variable of postural control was postural sway velocity of the center of gravity during both double leg and single leg stances. However, limits of stability (LOS) variables were calculated as well, including reaction time, movement velocity, directional control, endpoint excursion and maximal excursion. Over the course of twenty-six weeks, fortyfour males (18%) and thirty-two females (20%) reported ankle sprains.[73, 74] The analysis of the postural control data yielded interesting results. While the primary variable for postural stability (sway velocity) did not differ between injured and uninjured groups in either the male or female groups, there were significant findings among the injured and uninjured populations when separated by gender. In the male population, there was a significant difference in directional control using the limits of stability measures of the Neurocom ($p = 0.037$).[73] The female population demonstrated significant differences between endpoint excursion ($p = 0.033$) and maximal excursion measures ($p = 0.020$) for injured females versus uninjured females.[74]

The inconsistency among results utilizing static postural tasks may be due to the fact that a single leg balance task may not be functionally challenging enough to fully replicate the tasks required for athletic performance or activity. All of these studies, including those that found conflicting results, recruited athletes as subjects or at least healthy, active individuals. Static tasks may not be sufficiently challenging in the athletic or active populations to identify any significant differences between injured and uninjured populations, prospectively. This reiterates the need to use dynamic measures of postural stability as potential risk factors for injury. The studies discussed in the following section used dynamic tasks to measure postural control as a predictor of injury and had more agreeable results.

2.2.2 Dynamic Postural Control as a Risk Factor for Injury

The number of studies utilizing dynamic postural stability tasks as a risk factor for injury is far less extensive than the number of studies using only static tasks. The Star Excursion Balance Test (SEBT) is a commonly utilized clinical tool in measuring dynamic postural stability.[21, 45] Plisky et al[45] used the SEBT to determine if performance was predictive of ankle injury.[45] The study prospectively followed 235 male and female high school basketball players over the course of the winter sports season.[45] Before the start of the season, all athletes performed a modified SEBT. Maximum reach distance (MRD) was measured in the anterior, posteromedial and posterolateral directions, and was also used to calculate a composite reach distance.[45] Fifty-four players (23%) sustained a lower extremity injury, including both ankle and knee sprains.[45] Decreased normalized right leg anterior MRD, decreased normalized bilateral MRD in the posteromedial and posterolateral directions, and composite bilateral MRD were all found to be predictive of injury.[45] In addition, the results of this study reported that female athletes demonstrating a normalized right leg composite MRD less than or equal to 94% of their limb length were over six times more likely to sustain a lower extremity injury ($p < 0.05$).[45]

Paterno et al[43] measured dynamic postural stability in athletes who sustained ACL injury and underwent subsequent repair (ACLR) using a Biodex Stability System.[43] This balance system requires participants to stand single-legged on an uneven, dynamic platform, and generates an instability score based on degrees of deflection as the platform moves. Fifty-six athletes were measured for postural stability, kinetics and kinematics during a drop vertical jump task, and AP-knee joint laxity.[43] Athletes were monitored for one year.[43] During that time, thirteen athletes experienced a second ACL rupture.[43] The results of this study showed a significant association between higher stability scores (worse postural stability) and second injury ($p < 0.05$).[43] The injured group demonstrated a mean degree of deflection stability score of $4.07° \pm 2.06°$ while the uninjured group demonstrated a mean degree of deflection stability score of $3.63° \pm 1.58°$.[43] This study found that participants with worse dynamic postural stability were twice as likely to sustain a second injury compared to those with comparatively better postural stability.[43] Similarly, Vrbanic[66] found that the Balance Index Score was predictive of primary

ACL injury in Croatian female handball players.[66] Fifty-two players' dynamic postural stability was measured using a Sport KAT 2000 Balance System, which computed a Balance Index Score (BIS) for each subject.[66] Similar to the stability score in the previous study, a higher BIS indicates worse dynamic postural stability. Over a 5-year long time period, seven of fifty-two athletes sustained an ACL injury.[66] The study found that the athletes that sustained ACL injury or were no longer involved in sports had higher BIS scores at the time of testing, and suggested that worse dynamic postural stability was predictive of ACL injury.[66]

In summary, there is a need for further prospective research that utilizes measures of dynamic postural stability tasks as potential predictors of injury in order to support the theory that postural stability is actually a risk factor for lower extremity injury. While the few studies measuring dynamic postural stability as a predictor of injury have come to similar conclusions, perhaps researchers could more comprehensively evaluate overall postural control by utilizing different dynamic tasks. Thus, it is important to examine the relationship among these tasks to determine if all measurements of dynamic postural control are assessing the same components of the sensorimotor system and if different tasks challenge the sensorimotor system in different capacities.

2.3 THE SENSORIMOTOR SYSTEM

The sensorimotor system is a subcomponent of motor control system, and is responsible for incorporating all afferent and efferent information, as well as the central integration and processing components involved in maintaining functional joint stability and overall postural control.[48] The maintenance of functional joint stability is accomplished through a complementary relationship between static components, such as ligaments and bony geometry, and dynamic components. The dynamic components include the feedforward and feedback components that control the skeletal muscle crossing the joint. Feedback control is the stimulation of corrective response within the corresponding system after sensory detection. Postural control requires the combination of both the feedforward and feedback control systems.[49]

2.3.1 Components of the Sensorimotor System

The regulation of postural equilibrium is highly dependent the individual components of the sensorimotor system, particularly the organs responsible for joint proprioception and neuromuscular control.[49] Proprioception has been defined as the afferent information from "proprioceptors" located in the "proprioceptive field".[60] For the purpose of this study, these "proprioceptors" can be defined as the cutaneous, ligamentous, capsular and musculotendinous mechanoreceptors located within and surrounding the joint.[60] Of these cutaneous, ligamentous, capsular and musculotendinous receptors, there are different types of mechanoreceptors with different sensitivities to stimulation.[34] In addition, these different types of receptors also vary in their speed of adaptation.[34, 49, 77, 78] It is difficult to measure the isolated stimulation of a specific type of mechanoreceptor; however, there is research to propose that static and dynamic tasks may challenge components of the sensorimotor system differently.[7, 51, 56]

The different types of ligamentous, cutaneous and capsular mechanoreceptors include Ruffini receptors, Pacinian corpuscle, Golgi-tendon organ-like endings and free nerve endings.[49, 77, 78] Ruffini receptors are low threshold and slow adapting, stimulated by mechanical deformation of the tissue.[49, 77, 78] They are sensitive receptors that are nearly always stimulated, responding to changes in tissue tension.[77, 78] However, the Ruffini are also slow adapting to stimulus, categorizing the receptors as both static and dynamic, contributing to both static and dynamic tasks of neuromuscular control.[77, 78] Conversely, the Pacinian corpuscles are fast adapting.[49, 77, 78] However, Like the Ruffini receptors, the Pacinian corpuscles are also low threshold, but because of their fast adapting characteristics, Pacinian corpuscles are classified strictly as dynamic mechanoreceptors, responding to fast acceleration or deceleration of joint movement.[77, 78] Golgi tendon organ-like endings and free nerve endings can also be found in ligament and joint capsule tissue.[49, 77, 78] The Golgi tendon organ-like endings are very high threshold and slow adapting, and are completely inactive when the joint is immobile.[77, 78] These mechanoreceptors only respond to extreme changes in joint position.[49, 77, 78] The free nerve endings are also high threshold but non-adapting, contributing to pain sensation. [77, 78] Ligaments and capsular tissue are considered static components of the sensorimotor system, however the mechanoreceptors located within these tissues plays a significant role in the activation of the dynamic components of the sensorimotor system.[49, 77, 78]

Muscular tissue contains Golgi tendon organs (GTOs) and muscle spindles.[49, 50, 77, 78] The GTOs are located in series with the musculotendinous fibers of the tissue and are stimulated upon the stretch or lengthening of the tissue.[50] The GTOs are very low threshold and are highly sensitive to stimulation, providing the Central Nervous System (CNS) with continuous feedback concerning the active muscle tension.[49, 50] Muscle spindles are located in parallel with the contractile muscle fibers and respond to change in muscle length reflexively.[50] The muscle spindles are responsible for providing feedback to the CNS regarding muscle length and rate of change in length.[50] Contained within the muscle spindles are specialized nerve endings that wrap around muscle fibers called intrafusal fibers.[50] These fibers are innervated by the gamma motor neurons which are sensitive to changes in the other peripheral mechanoreceptors.[30, 50] As the peripheral area is stimulated, the gamma motor neuron is activated and causes muscle fibers surrounding the intrafusal fiber to contract, thus stretching the muscle spindle and making it more sensitive.[30, 50]

The afferent information collected from the cutaneous, ligamentous, capsular and muscular tissue is then relayed to the CNS.[49, 50] The CNS then processes that information and produces the efferent information necessary for the appropriate muscular response.[49, 50] While typically these different types of mechanoreceptors are classified as static or dynamic, it is clear that mechanoreceptors of the static components and the mechanoreceptors of the dynamic components are very much interrelated, and perhaps postural stability cannot be defined as strictly static or dynamic. In addition, the static components and dynamic components of the sensorimotor system work synergistically to maintain postural control during different tasks.[49, 50] Therefore, it seems that two types of dynamic tasks with different goals, such as maintaining a base of support through a perturbation compared to a jump task, would each provide unique challenges to the sensorimotor system.

2.3.2 The Sensorimotor System and Postural Stability

The mechanoreceptors of the static and dynamic components accomplish the first step necessary in the maintenance of postural stability, providing afferent information to the spinal cord and brain stem so the CNS can organize the incoming sensory information.[49] The CNS then determines the timing, direction and amplitude of the corrective actions necessary to maintain postural equilibrium, and coordinates the generation and execution of the appropriate motor responses in the appropriate sequence.[49] This is the process necessary for maintaining postural equilibrium.[49] While the process for maintaining postural stability should be the same for both static and dynamic tasks, the efferent information transmitted to the CNS may be collected from different sensorimotor components, or different sensorimotor organs may contribute in different capacities during the different tasks.

The process of maintaining postural equilibrium also requires both the feedback and feedforward controls of the sensorimotor system.[49] Feedback control is defined as the stimulation of corrective response within the corresponding system after sensory detection.[49] For example, if an individual takes a step on an uneven surface, the mechanoreceptors of the ankle soft tissue will be activated and the CNS will collect and organize all efferent information and initiate the appropriate musculoskeletal response to maintain postural equilibrium.[30, 40, 48] Conversely, feedforward controls are defined as the anticipatory actions occurring before the sensory detection of homeostatic disruption.[49] An example of feedforward control can be seen in the muscle activation during a vertical drop landing. Hamstring muscle activation occurs during the preparatory phase before landing. As the primary dynamic stabilizer of anterior translation of the knee, hamstring activation helps to reduce the load placed on the anterior cruciate ligament in the knee.[6]

The maintenance of postural equilibrium appears to be related to the risk of injury.[34] An individual that demonstrates poor postural control may be placed in more vulnerable positions because they cannot correct for disturbances appropriately or efficiently enough, and therefore, may be at risk for injury.[34, 50] Furthermore, the different sensorimotor organs seem to contribute to static and dynamic tasks in different capacities. A slower adapting, lower threshold mechanoreceptor will most likely play a more prevalent role in maintaining static balance compared to a faster adapting mechanoreceptor, which likely contributes more to maintaining postural stability during functional and dynamic tasks. While there is sufficient research to demonstrate the lack of relationship between static and dynamic tasks, the relationship between different types of dynamic tasks remains unknown. The lack of correlation demonstrates that the sensorimotor organs may be challenged differently during static versus dynamic tasks of postural stability, and therefore perform in different capacities during these separate tasks to maintain postural equilibrium.

2.4 THE RELATIONSHIP POSTURAL STABILITY TASKS

2.4.1 Relationship Between Static and Dynamic Postural Stability Tasks

There are several studies to examine the relationship between different static and dynamic tasks.[7, 41, 51, 56] However, the results of these studies are not in agreement. While two of the earlier studies found weak, but still significant relationships between static and dynamic tasks,[7, 41] the later studies found no relationship between measures of static and dynamic postural stability.[51, 56] These conflicting results could potentially be due to the types of different tasks used to measure static and dynamic postural stability.

Nakagawa et al[41] examined the postural control of healthy individuals and individuals with recurrent ankle sprain using static, dynamic and clinical tests. In this study, researchers measured static balance as the total COP excursion during a unilateral stance.[41] Dynamic balance was assessed using a novel task, instructing subjects to take a lateral step onto an unstable surface on top of a force plate and measured total COP excursion as well.[41] Finally, functional balance was tested utilizing the four diagonal directions of the SEBT.[41] While the primary purpose of this test was to compare the postural stability in a healthy population to the postural stability in a population with recurrent ankle sprains, the results of this study also demonstrated weak but still statistically significant relationships between static and dynamic tasks ($r = 0.10$), static and functional tasks ($r = 0.05$) and between dynamic and functional tasks ($r = 0.12$).[41] These results are not completely surprising, as one would expect the correlation between the static and functional tasks to be weakest, and the correlation between the dynamic and functional tasks to be strongest. Additionally, these results support the idea that all tasks of postural stability are regulated by the same sensorimotor system and are somewhat interrelated, but the weakness of these relationships also support the theory that perhaps these tasks challenge different components of the same sensorimotor system. What is surprising is the fact that these tasks were found to be related, while similar studies performed at a later time found that no relationship existed between static and dynamic tasks. Again, this discrepancy may be due to the different variables used to measure postural stability in different studies. This disagreement among results may also be due to the fact that this study calculated correlation values using data from both healthy and pathological populations. While these assessments may be sensitive enough to find a significant correlation in a pathological population, they may still not be sensitive enough to do the same in a healthy population.

Clark et al[7] found similar results to Nakagawa when comparing static balance, measured using a single leg stance and a modified BESS (mBESS) test, with dynamic balance, measured using the SEBT.[7] The single leg stance was measured using the protocol set forth by Trojian et al[64], grading the trial as either pass or fail, and not utilizing any continuous data variables.[64] The results of this study showed a significant, but weak relationship between the SEBT and both the single leg stance task ($p = 0.025$) and the mBESS test ($R = -0.35$).[7] However, there is no way to compare the relationships between the SEBT with the SLBT and the SEBT with the mBESS to determine if one was stronger than the other because the SLBT was measured as pass or fail. It is still important to point out that this is study also demonstrated a significant relationship between static and dynamic measures. The disagreement among these results and later tests also may be due to the method of measuring static postural stability. While the purpose of this test was to utilize clinical measures of postural stability, it is generally agreed upon that force plate measures are the gold standard of measuring static postural stability.[14, 38] Although the clinical method of measuring static postural stability has been demonstrated to be a reliable measure of predicting ankle sprain,[64] it may not be a sensitive enough measure to appropriately examine the relationship between static and dynamic postural stability, thus contributing to the disagreement of results among this study and later studies.

A later study investigated the relationship between three single leg assessments of postural stability.[51] Riemann et al[51] measured static postural stability as center of pressure velocity, using firm and multiaxial surfaces, with eyes both open and closed.[51] Dynamic postural stability was measured using the SEBT and a single leg hop stabilization test (SLHT).[51] The SLHT data was measured using two variables, the landing phase during the initial landing of the jump task, and the balance phase that includes the five seconds following the landing.[51] Unlike the previous studies, Riemann et al[51] found no significant relationships existed between the measures of static postural stability and either of the dynamic postural stability measures.[51] These results support the theory that maintaining static balance and stabilizing after a voluntary action may require different mechanisms of maintaining postural equilibrium, and therefore are not related. Similarly, Sell et al[56] examined the relationship between static and dynamic postural stability utilizing force plate measures.[56] Static postural stability was measured utilizing standard deviation of force measures in the three directional planes, while dynamic postural stability was measured using DPSI.[56] The results of this study also demonstrated a lack of relationship between any of the static and dynamic measures.[56]

The outcomes of these previous studies demonstrate that performance of static tasks may not be related to the performance of tasks of dynamic postural stability. Additionally, each of these studies suggested that the sensorimotor components required for maintaining steadiness or static balance are different from the components required for quickly establishing a base of support during a dynamic task. While two of the studies did report the correlation values between different dynamic tasks, no study has compared the SEBT to DPSI. Furthermore, no study has examined the relationship of each compared to force measures of static postural stability to see if one task is more related to static balance than the other.

2.4.2 The Relationship Between Dynamic Tasks

Both Nakagawa et al[41] and Riemann et al[51] investigated the relationship between different tasks of dynamic postural stability.[41, 51] The first study compared dynamic postural stability during a lateral step onto an unstable surface to performance on the SEBT, and found that the two measures had a very weak, but still significant relationship ($r = -.12$).[41] The authors proposed that this relationship may show that the two tasks are related, but because the correlation is weak, the tasks may still be dependent on different sensorimotor components.[41] However, what is important to note in this study, are the correlation values for each of the dynamic tasks with the static task. The relationship between COP measures during the static task and COP measures during the dynamic, lateral step task revealed a Pearson's r-value of 0.10.[41] The relationship between COP measures during the static task and performance on the functional, SEBT task revealed a Pearson's r-value of 0.05.[41] These results are interesting as it would be expected that the SEBT, which has a stationary base of support, would be more strongly correlated with static postural stability measurements, when compared to a more dynamic task that requires the quick stabilization after a voluntary movement. One reason for this discrepancy may be that the lateral step onto a force plate is not dynamic or functional enough to fully challenge the sensorimotor system for the population of subjects. Secondly, it has been demonstrated that COP force plate measures are not as sensitive as the standard deviation of force measures.[14] Thus, there is a need to evaluate dynamic tasks utilizing a more challenging dynamic task and more sensitive measures.

On the contrary, Riemann et al[51] found no relationship between any of the SEBT or SLHT variables. These results support the hypothesis of the current study. The SEBT requires the participant to maintain a static base of support while voluntarily disturbing that base of support as maximally as possible.[32, 51] The SLHT requires both the quick stabilization after a jump task and the balance required afterwards to remain in the single leg stance, and appears more challenging and functional compared to the lateral step task from the Nakagawa et al[41] study.[41, 51] In the Riemann et al[51] study, the SLHT task was measured as two scores, landing errors and balance errors.[47, 51] The landing errors scores were determined based on the number of errors that occurred during the landing immediately after the jump task. The balance error scores were determined based on the number of errors that occurred for the five seconds after the subject had established a stable base of support upon landing.[47, 51] It should not be surprising that the relationships between the balance scores and other variables were not the same as the relationships between the landing scores and other variables. Furthermore, neither the balance score nor landing score were correlated with the performance on the SEBT. In fact, the SEBT was not correlated with any of the other tasks of postural stability.

The result of this study is both expected and surprising. It should be expected that there is no relationship between the purely static measurements, such as the single leg stance and multiaxial surface stance, and the purely dynamic tasks, the SEBT and the SLHT. Similarly, it should be expected that all measures of static postural stability are related, with the exception of the single leg stance on a firm surface with eyes closed (FIEC) and single leg stance on a multiaxial surface with eyes open (MAEO). The results investigating the relationship between the dynamic tasks are more surprising. Because the balance score of the SLHT is based on the time between hops when the subject is maintaining a single leg stance after landing, and before taking off for the next hop, it could be assumed that this score is static.[47] However, the balance score was found to be correlated with only the landing score from the same test. This is surprising considering the landing score from the SLHT is based on the stabilization after the hop, and should be considered a dynamic score.[47] The two variables are related even though they are considered static and dynamic, respectively. The possible cause for this result may be due to the fact that these scores are based on the same task. It could be assumed that if the landing score of a hop is high, it could be due to a bad hop, rather than diminished postural stability. In this case, the maintenance of postural equilibrium after the landing may also be increasingly difficult because of the bad hop. Thus, these two tasks could be related, but it may not be due to the variables measuring similar components of postural control.

These results demonstrate the potential issue with the SLHT. While a useful and effective clinical tool, the SLHT measures two different types of variables, the landing score (dynamic) and balance score (static), and is not an all-encompassing assessment of dynamic postural control. A different jump task assessment, such as DPSI, could be a more appropriate as it is measured based on the GRF data upon landing and for the time balancing after landing. In addition, DPSI is calculated completely from force plate data, and may be more objective than having an examiner score a landing, such as in the SLHT. Thus, there remains a need to compare a truly dynamic and objective task, such as DPSI, with the SEBT to determine if there is any relationship between the two assessments.

2.5 METHODOLOGICAL CONSIDERATIONS

This section will address specific considerations for the methodology of this study. More extensive details regarding the procedures for each of the postural stability tasks can be found in the Methodology section of this thesis.

2.5.1 Single Leg Balance Test

The SLBT is a commonly utilized assessment for measuring balance and static postural stability. While there are clinical methods for using the single leg balance test as a assessment of postural control,[4, 64] it is agreed that force plate procedures are the "gold standard" in measuring static postural stability.[14, 15, 38] In addition, Goldie et al[14] found that force variables were more reliable and sensitive than center of pressure measurements in the same axes, and that force measurements in the medial-lateral (ML) direction were the most accurate in discriminating between difficulty of stances.[14] Another study also demonstrated that standard deviation (SD) of force measurements in the ML direction were the best predictor for measuring steadiness in a single leg stance of the dominant leg with the eyes open.[15]

Therefore, for the purpose of this study, static balance was measured using the SLBT protocol set forth by Goldie. This study only utilized the dominant leg stance with the eyes open. Because the SEBT and DPSI tasks were performed with the eyes open as well, visual input was included for all three tasks. The variable being measured and used for data analysis was the standard deviation in force measurements in the ML direction.[14, 15] The NMRL has previously found this method to be accurate and reliable, demonstrating ICC values ranging from 0.71 – 0.93.[56, 57, 59]

2.5.2 Star Excursion Balance Test

The SEBT is a commonly utilized clinical tool for measuring dynamic postural stability.[21] The reason that the SEBT was selected for this study was because the task is one of a kind. There are no other tasks that assess dynamic postural stability that maintain the base of support while also trying to maximally disturb it through a series of reaches. Originally, the SEBT incorporated eight reach directions (anterior, anteromedial, medial, posteromedial, posterior, posterolateral, lateral, and anterolateral),[32] but more recent studies have demonstrated that the maximum reach distances (MRD) in each of the eight directions are highly correlated with each other.[17, 21, 24, 44] It has been recommended that measuring the MRD in the anterior, posteromedial and posterolateral directions may be a more efficient, but still accurate protocol.[17, 44] A previous study has also utilized the sum of these three directional measurements to calculate a SEBT composite score as a risk factor for injury.[45] Because the purpose of this study is to compare the SEBT to another multiplanar task, DPSI, a composite score was calculated for correlational analysis. Another concern regarding the methodology for the SEBT is the learning effect and number of practice trials required for each participant. Robinson and Gribble[52] found that MRD measurements and kinematic data stabilized after participants were provided with four practice trials.[52]

An additional consideration for measuring the SEBT is the starting point or reference point of the stance leg. At this time, there is no general consensus as to where the stance foot should be aligned relative to the grid.[21] Several studies have used the reference point as the bisection of the malleoli, or geometric center of the foot lined up with the intersection of the grid,[18, 20, 24, 32, 42] while others have simply utilized the most distal aspect of the great toe at the intersection of the grid.[45] However, it is agreed that the most important consideration when selecting a starting point of the SEBT is that is remains consistent for each trial and each participant.[21]

A recent study evaluated the concurrent validity of measuring MRD using two examiners and measuring MRD using a motion analysis system.[3] The results of this study found that using two examiners and visual estimation was nearly as accurate as the motion analysis system.[3] This study also examined the difference in sensitivity when measuring MRD normalized to leg length compared to total height. The results found that normalizing MRD measures to height was a more accurate and sensitive measure when discriminating between healthy individuals and individuals with chronic ankle instability.[3] However, the majority of studies utilizing the SEBT as a postural stability assessment have normalized MRD measurements to leg length and found significant results.[21] Therefore, for the purpose of this study, MRD was normalized to leg length so the results of this study are consistent with results from the majority of other studies utilizing the SEBT. MRD measurements were measured in the anterior, posteromedial and posterolateral directions, and were obtained by using two examiners and visual estimation.[17, 45]

2.5.3 Dynamic Postural Stability Index

DPSI is a more recently validated force plate measurement methods for assessing dynamic postural stability. Developed by Wikstrom, DPSI is based on the SLBT and SLHT tasks with the theory that dynamic postural stability is interrelated with landing kinematics and muscle activation patterns.[72] While there are other jump task measure of dynamic postural stability, such as the SLHT and Time to Stabilization (TTS), DPSI was selected because it provides a sensitive, objective measure calculated from force plate data and also provides a composite score calculated from the three directional indices.[47, 54, 69]

The original protocol for DPSI required a jump task normalized to maximum vertical jump height.[72] However, the NMRL developed a protocol including a jump task normalized to subject height, rather than vertical jump height. The NMRL procedures for measuring DPSI are based on the LESS protocol set forth by Padua et al[4], and were created in order to minimize necessary equipment, and for the more related purpose of incorporating greater deceleration forces upon landing.[56, 57, 59] The current study utilized the protocol established and tested previously by the NMRL, which has been found to be reliable, demonstrating an ICC value of 0.86.[56] The DPSI composite score was compared to the average, composite MRD measured from the SEBT.

3.0 METHODOLOGY

3.1 EXPERIMENTAL DESIGN

This study utilized a cross-sectional, correlational design. The purpose of this study was to determine if there is a significant linear relationship between two different assessments of dynamic postural stability within a healthy population. In addition, this study investigated if one test of dynamic postural stability was more strongly associated with a test of static postural stability compared to a different test of dynamic postural stability.

3.2 PARTICIPANTS

3.2.1 Subject Recruitment

This study was approved by the Institutional Review Board at the University of Pittsburgh prior to implementation of all research procedures. Individuals were recruited from the University of Pittsburgh and surrounding community. Informational flyers were posted at the University of Pittsburgh fitness facilities and common areas of academic and fitness buildings. Individuals that were interested in participating contacted the Neuromuscular Research Laboratory (NMRL) of the University of Pittsburgh. Eligibility for the study was determined after reviewing inclusion and exclusion criteria. All testing was performed at the NMRL.

3.2.2 Subject Consent

Each participant was provided with and signed an informed consent in accordance with the University of Pittsburgh Institutional Review Board prior to any testing procedures. Each participant was given the opportunity during this process to ask any questions concerning their participation prior to taking part in the study.

3.2.3 Inclusion Criteria

Individuals must be between the ages of eighteen to thirty-five and considered physically active. Physically active was defined as individuals self-reporting a score of five or greater on the Tegner Activity Scale (Appendix A).[63] Physically active adults were selected based on the specific aims of this study.

3.2.4 Exclusion Criteria

Individuals were not included if they meet the following criteria:

- History of injury to the dominant leg knee, ankle, hip or lumbar spine in the six months prior to testing
- History of surgery or fracture of the dominant leg being tested in one year prior to testing

- Any sort of balance or vestibular disorder, or any other disorder having an effect on neuromuscular control
- Any history of concussion or head injury
- Taking medication known to affect balance
- Female participants could not knowingly be pregnant

3.3 SAMPLE SIZE CALCULATION

To the best of this author's knowledge, there is no previous study that determined the correlation between the variables being examined in this study. Using the G*Power 3.1.7 (Heinrich Heine Universitat, Dusseldorf, Germany) sample size calculator, a sample size of 19 subjects would achieve a 81.4% power to detect a difference of -0.60 between the null hypothesis correlation of 0 and the alternative hypothesis correlation of 0.60 using a two-sided hypothesis test with a significance level set *a priori* at $\alpha=0.05$.[46] To account for attrition and potential data loss, N=21 subjects were needed to participate in this study.

3.4 INSTRUMENTATION

3.4.1 Anthropometric Measurements

Height was measured using a stadiometer (Seca North America, East Hanover, MD). Mass was measured using a weight scale (BOD POD Version 5.2.0, COSMED USA Inc., Chicago, IL).

Lower extremity length was measured from the ASIS to the medial malleolus using a tape measure.

3.4.2 Force Plate

A piezoelectric force plate (Model 9286A, Kistler Instrument Corp., Amherst, NY) was used to measure ground reaction force (GRF) data during the SLBT and DPSI tasks. Static postural stability was measured at a frequency of 200 Hz while dynamic postural stability data was measured at a frequency of 1200 Hz. For this study, GRF data in all three planes was used to calculate both SLBT standard deviations and DPSI scores based on the previous research.[14, 72] Analog data from the force plate was converted to digital signal using an A to D board and recorded utilizing the Vicon Nexus Software 8.5 application (Vicon Motion Systems LTD. Centennial, CO).

3.4.3 Star Excursion Balance Test

Three lines of 120 cm athletic tape was laid directly on the floor to create a grid. The lines extended at 120° increments from the center of grid where the lines intersect. Maximum reach distance was measured using a tape measure from the center of the grid.

3.5 TESTING PROCEDURES

The order of testing was randomized for each participant using Latin Squares to limit any learning effect one test may have on another.

3.5.1 Single Leg Balance Test

The SLBT procedures were based upon the protocol implemented by Goldie et al.[14] Previous studies have found this protocol to demonstrate moderate to good reliability (ICC = 0.759-0.879).[56] Participants were instructed to assume a single legged stance with the dominant leg in the center of the force plate, flexing the non-stance leg at the knee and hip to bring the non-stance foot to the height of the stance leg ankle, with hands on the hips and eyes open. Participants remained in that position for 10 seconds until instructed by the examiner to relax at which point the participant can return to a bipedal stance. Trials were included if the participant touches down with the non-stance leg as long as it is on the force plate. Trials were discarded and repeated if:

- The participant touches down with non-stance leg occurs on the ground outside of the force plate
- The non-stance limb touches the stance limb at any point during the trial.

Participants were provided with at least three practice trials before performing three 10 second testing trials, but may take more until they feel comfortable with the task. Between testing trials, participants were provided with a 30 second rest.

3.5.2 Star Excursion Balance Test

For the SEBT, procedures were based off of those implemented by Plisky et al.[45] Originally the SEBT incorporated eight reach directions;[32] however, in order to reduce the redundancy of the task and risk of fatigue, subjects were only be required to reach in three directions (anterior, posteromedial and posterolateral).[21, 29, 45] Research has found this protocol to be reliable with ICC values ranging from 0.84 – 0.92.[39] Subjects were instructed to stand with their dominant leg in the starting position defined as the center of the grid, with the medial and lateral malleoli aligned with the medial-lateral line of the grid. While maintaining a single leg stance, the subject was instructed to reach with their non-stance leg as far as possible in the prescribed direction along the line of the tape, tapping down on the tape with their great toe of their non-stance leg (Figure 1). To control for stance foot variation, one examiner watched the stance foot to make sure it is not lifted or moved, while another examiner measured the MRD from the center of the grid in centimeters. The order of testing was standardized for each participant to control consistency of the administration of the test, first reaching in the anterior direction, followed by the posteromedial direction, then posterolateral direction.[18] Trials were completed after the subject reached in the three directions then returned the non-stance leg to the starting position. Participants were provided with as much rest as needed before performing the next trial.[32] Trials were discarded and repeated if:

- The subject fails to maintain the stance position on the dominant foot,
- The subject moves or lifts the stance foot from the starting position,
- The subject touches down with the non-stance leg off of the foot, or
- The subject fails to return to the starting position.[21]

Participants were provided with at least four practice trials or as many as necessary before feeling comfortable with the task.[24] Data from three successful trials were used for data reduction and analysis.

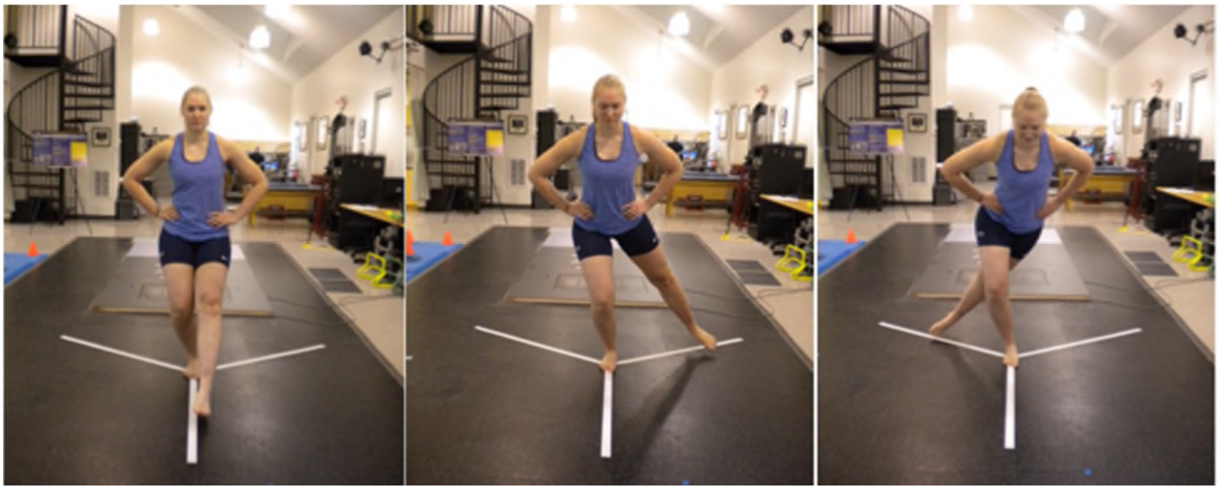

Figure 1. Performing the Modified Star Excursion Balance Test

3.5.3 DPSI Procedures

The protocols for the DPSI jump tasks were based off of previous research which has been demonstrated ICC values ranging from 0.86 to 0.96.[56, 72] For the jump task, participants begin in the starting position standing on two legs at a distance 40% of their height away from the edge of the force plate. Subjects were instructed to jump forward off both legs and over a 12-inch hurdle placed halfway between the starting point and edge of the force plate, land on their dominant leg with their hands on their hips stabilizing as quickly as possible, and holding that position until cued by the tester. Trials were discarded and repeated if:

- The subject loses their balance and touches down on the force plate or ground with the non-stance limb,
- The subject fails to stick the landing (rotates stance leg or hops),
- The subject does not land with their entire foot on the force plate, or
- The subject hits the hurdle.

Participants were required to complete at least three practice trials, but may take as many as necessary to feel comfortable with the task before performing five successful testing trials.[56]

3.6 DATA REDUCTION

3.6.1 SLBT Measurements

Force plate data were passed through a zero-lag 4th order low pass Butterworth filter with a 20 Hz cutoff frequency and processed using a custom MATLAB (v7.0.4, Natick, MA) script file.[56] SLBT variables were calculated as the standard deviation of ground reaction forces (GRF) data in the anterior-posterior (APSD), medial-lateral (MLSD) and vertical (VSD) directions using the equation:

$$SD = \sqrt{[\Sigma(x - X)^2 \div (n-1)]}$$

where x is equal to each force measurement, X is equal to the mean of all force measurements in the data set, and n is equal to the number of measurements in the data set. The average standard deviations were calculated in each direction from each of the ten-second trials.

3.6.2 SEBT Maximal Reach Distance

SEBT reach measurements were calculated as a percentage normalized to leg length.[21, 24] The maximum reach distance was divided by the leg length measurement and multiplied by 100 to calculate the normalized maximum reach distance (MRD). Normalized MRD was calculated for each of the three directions of the SEBT task. The average, normalized MRD was calculated from each trial for each direction. The composite SEBT score was calculated as the sum of the each average, normalized MRD divided by three.

3.6.3 DPSI Composite Scores

The first three seconds of GRF data after initial contact were used for data processing. Initial contact was defined as when the vertical GRF force exceeds 5% of the subject's body mass. Force plate data were passed through a zero-lag 4^{th} order low pass Butterworth filter with a 20 Hz cutoff frequency and processed using a custom MATLAB (v7.0.4, Natick, MA) script file.[56] DPSI composite scores were calculated for each of the jump task trials using the following calculation:

$$\text{DPSI} = (\surd\ [\Sigma(0\text{-}x)^2 + \Sigma(0\text{-}y)^2 + (\text{body weight-}z)^2/\text{number of data points}]) \div \text{body weight},$$

where x, y and z represent the standard deviation of GRF data in the x, y and z direction.[72] Average DPSI composite score were calculated from the five trials.

3.7 STATISTICAL ANALYSIS

Descriptive statistics were analyzed. Data were assessed for normality using a Shapiro-Wilk test. If data are normally distributed, the Pearson product moment correlation coefficient was used to assess the linear relationship between the normalized, composite MRD and the DPSI composite scores. The correlation coefficient indicated the strength of the relationship between performance on the SEBT and DPSI.[46] If data are not normally distributed, Spearman's rank correlation coefficients were used instead. The significance level was set *a priori* to $\alpha = 0.05$.

To achieve the secondary aim, correlation coefficients be calculated for the relationship between the SLBT measurements and normalized, composite MRD measured using the SEBT. Correlation coefficients were also calculated for the relationship between the SLBT measurements and average DPSI composite scores. The two correlation coefficients were compared to see if one dynamic task has a stronger linear relationship to static postural stability compared to the other. Since both correlations were computed using the same sample, they were compared using tests for two non-independent correlations.[68]

4.0 RESULTS

4.1 DEMOGRAPHIC INFORMATION

A total of 21 subjects volunteered to participate in this study. All 21 subjects met the necessary inclusion and exclusion criteria in the initial screening to undergo testing. Of those 21 subjects, two subjects' data were lost due to complications with the force plate during the collection process. A priori power analysis initially revealed that a sample size of N = 19 would be necessary to complete data collection. The data from the remaining 19 subjects were included for the analysis of this study.

Demographic data are presented in Table 1. The age range for the sample was 20-31 years old. Twelve subjects were female (63.2%) while seven subjects were male (36.8%). Leg dominance was defined as the preferred leg to kick a ball. Fifteen subjects (78.9%) were right leg dominant while four subjects (21.1%) were left leg dominant.

Table 1. Demographic Information

	Mean		SD	Median	LQ	UQ
Age (years)	22.2	±	2.6	21	21	23
Height (cm)	173.8	±	10.2	175	164	181
Weight (kg)	72.1	±	15.1	71.5	64.4	78.4
Leg Length (cm)	91.3	±	5.1	92.5	86.5	95

SD = Standard Deviation
LQ = Lower Quartile
UQ = Upper Quartile

4.2 RELATIONSHIP BETWEEN DYNAMIC TASKS

Dynamic postural stability was assessed using two different tasks, the Star Excursion Balance Test (SEBT) and the Dynamic Postural Stability jump task. During the SEBT, maximum reach distance (MRD) was measured from the center of the grid to the distance marked on the tape in the anterior, posteromedial and posterolateral directions. Average maximum reach distance was calculated from three trials, and then normalized to dominant leg length. The average, normalized MRD in the anterior direction was calculated to be 91.15 ± 5.56%. The average, normalized MRD in the posteromedial direction was calculated to be 84.31 ± 5.94%. In the posterolateral direction, the average, normalized MRD was calculated to be 73.90 ± 7.68%. The average, normalized composite MRD was calculated as the sum of the directional data, divided by three, to be 83.12 ± 5.32%. Results for all postural stability assessments can be found in Table 2. Sharpiro-Wilk analysis revealed that SEBT data were normally distributed. Individual subject MRD data are presented in Table 7, while normalized data are presented in Table 8 (Appendix B). The box plot of normalized data is represented in Figure 7 (Appendix B).

Dynamic postural stability was also assessed using a single leg jump-landing task. GRF data was utilized to calculate stability indices in three directional planes. A Dynamic Postural Stability Index (DPSI) composite score was calculated from the directional data. The average DPSI score among all subjects and trials was determined to be 0.336 ± 0.033. Results for all postural stability assessments can be found in Table 2. Sharpiro-Wilk analysis revealed that DPSI data were normally distributed. Individual subject data are presented in Table 9 (Appendix B). The boxplot of this data are represented in Figure 8 (Appendix B). Descriptive directional data and individual directional data are presented in Tables 10 (Appendix B).

A Pearson's Product Moment correlational analysis was utilized to determine the relationship between performances on the two dynamic tasks, the SEBT and DPSI jump task ($r = 0.145$, $p = 0.554$). Results of this correlational analysis can be found in Table 3. There was no significant relationship observed between SEBT measurements and DPSI composite scores. This relationship is represented in Figure 2.

Table 2. Postural Stability Measurements

	Mean		SD	Median	LQ	UQ
SLBT	2.69	±	0.88	2.38	2.11	2.75
SEBT	83.12	±	5.32	83.39	79.32	87.67
DPSI	0.336	±	0.033	0.328	0.306	0.362

SD = Standard Deviation
LQ = Lower Quartile
UQ = Upper Quartile
SLBT = Sample average GRFML standard deviation across 3 trials
SEBT = Sample average composite, normalized maximum reach distance across 3 trials
DPSI = Sample average composite score across 5 trials

Table 3. Correlational Analysis between SEBT Performance and DPSI Composite Scores

	SLBT	**SEBT**
SEBT	0.339β	-
DPSI	-0.035β	0.145α

α = Pearson Product Moment Correlation Coefficient
β = Spearman's Rank Correlation Coefficient
SLBT = Average GRF_{ML} standard deviation across 3 trials
SEBT = Average, composite, normalized MRD across 3 trials
DPSI = Average composite score across 5 trials
* = Significant p-value < 0.05

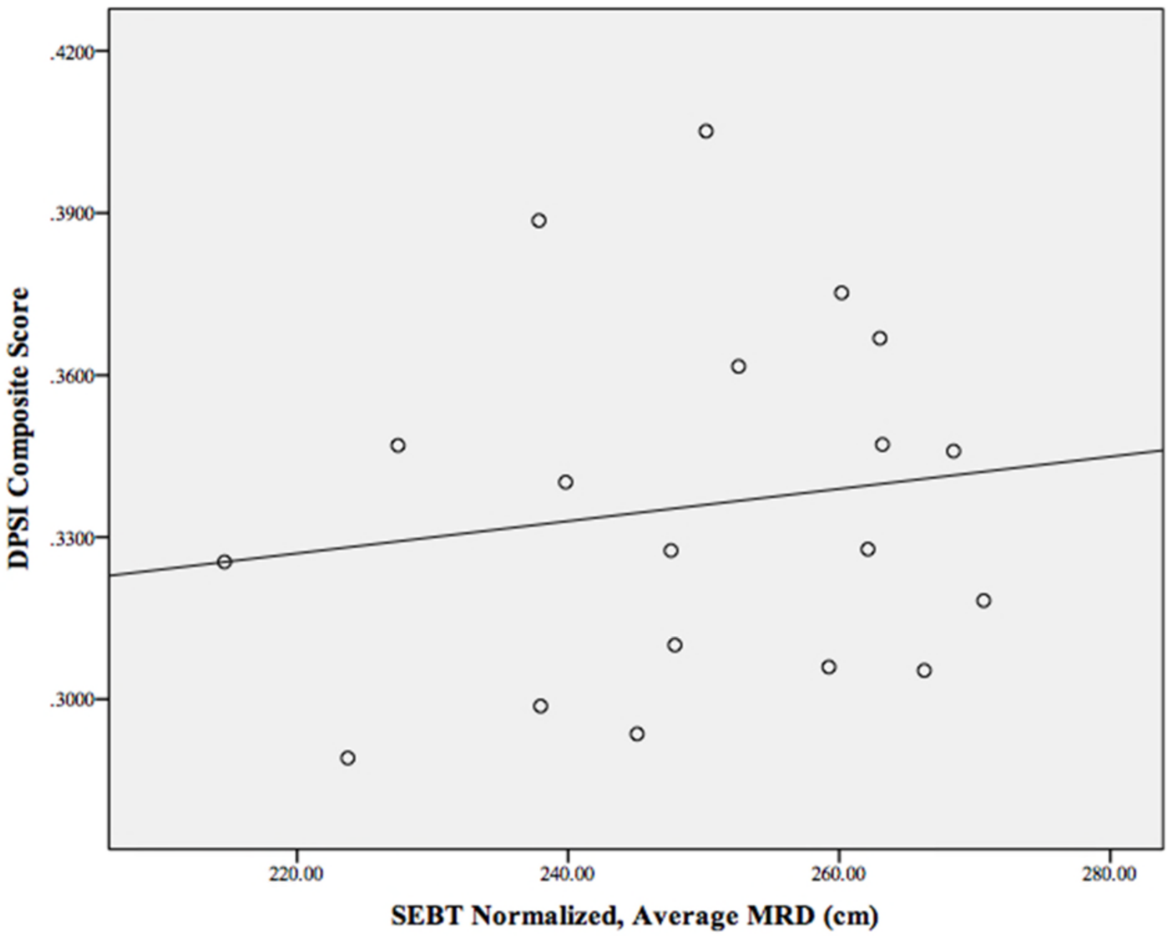

Figure 2. SEBT Average, Normalized MRD and DPSI Composite Scores

4.3 COMPARISON BETWEEN STATIC AND DYNAMIC MEASURES

Static postural stability was measured using the Single Leg Balance Test. GRF data was collected in three directional planes. The standard deviations of GRF data in the medial-lateral direction (ML) were used for analysis. The average GRF_{ML} score among all subjects and trials was determined to be 2.69 ± 0.88. The results for all postural stability assessments are presented in Table 2. Shapiro-Wilk analysis found that SLBT data violated the assumption for normality. Individual subject data are presented in Table 6 (Appendix B). The boxplot of this data is represented in Figure 6 (Appendix B).

A Spearman's Rho test was used to analyze the relationship between performances on the SLBT and SEBT ($r = 0.339$, $p = 0.156$), and again to analyze the relationship between performances on the SLBT and DPSI ($r = -0.035$, $p = 0.887$). The results of these correlational analyses can be found in Table 3. Neither correlation was found to be significant. The relationship between SLBT and SEBT measurements is presented in Figure 3, while the relationship between the SLBT measurements and DPSI composite scores is presented in Figure 4.

To achieve the secondary aim of this study, data was analyzed using Williams' test, as described by Weaver and Wuensch, for comparing two non-independent correlations that have a variable in common.[68, 75] Williams' test was utilized to determine if the relationship between the SLBT and SEBT measurements was significantly different from the relationship between the SLBT and DPSI composite scores; that is, is one dynamic task more strongly related to the static balance task compared to the other. Since Williams' test requires all data to be normally distributed, SLBT data were transformed using a base-10 logarithmic function. Following transformation, Shapiro-Wilk analysis found SLBT data were normally distributed. Pearson's

Product Moment correlational analysis was used to determine the relationships between transformed SLBT data and both of the dynamic tasks. The Pearson correlation coefficients were then utilized for Williams' test analysis. The results of this analysis can be viewed in Table 4. When the correlation between the SLBT and SEBT (r12) was compared to the correlation between the SLBT and DPSI (r13), no significant difference was found ($t = 1.443$, $p = 0.168$). The lower and upper limits listed in Table 4 represent the 95% confidence interval of r12 – r13.[79]

Table 4. Comparison of Correlations Between the SLBT and Dynamic Tasks

r12	**r13**	**r23**	**t**	**p-level**	**LL**	**UL**
0.413	-0.018	0.145	1.443	0.168	-0.170	0.942

r12 = Correlation between SLBT and SEBT measures
r13 = Correlation between SLBT and DPSI scores
r23 = Correlation between SEBT and DPSI scores
p-level = Set a priori to < 0.05
LL = Lower limit of 95% CI
UL = Upper limit of 95% CI

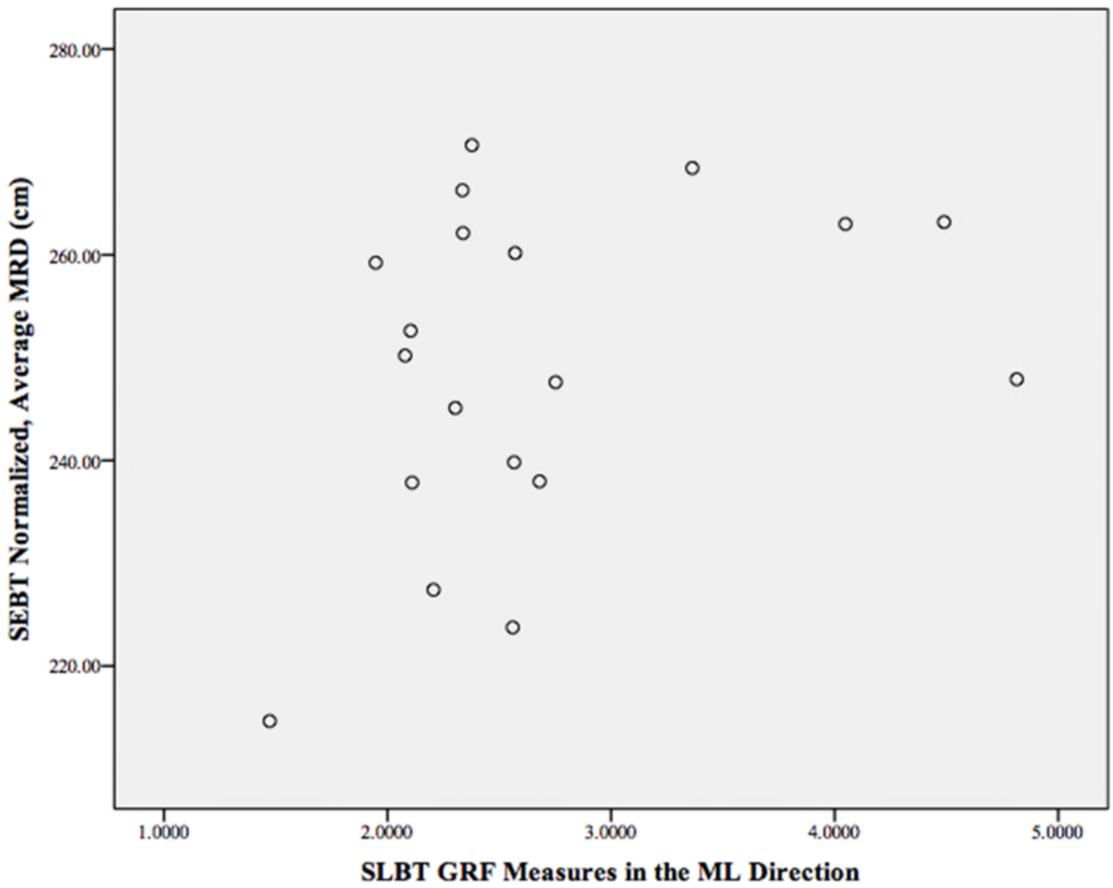

Figure 3. SLBT GRF Measurements and SEBT Average, Normalized MRD

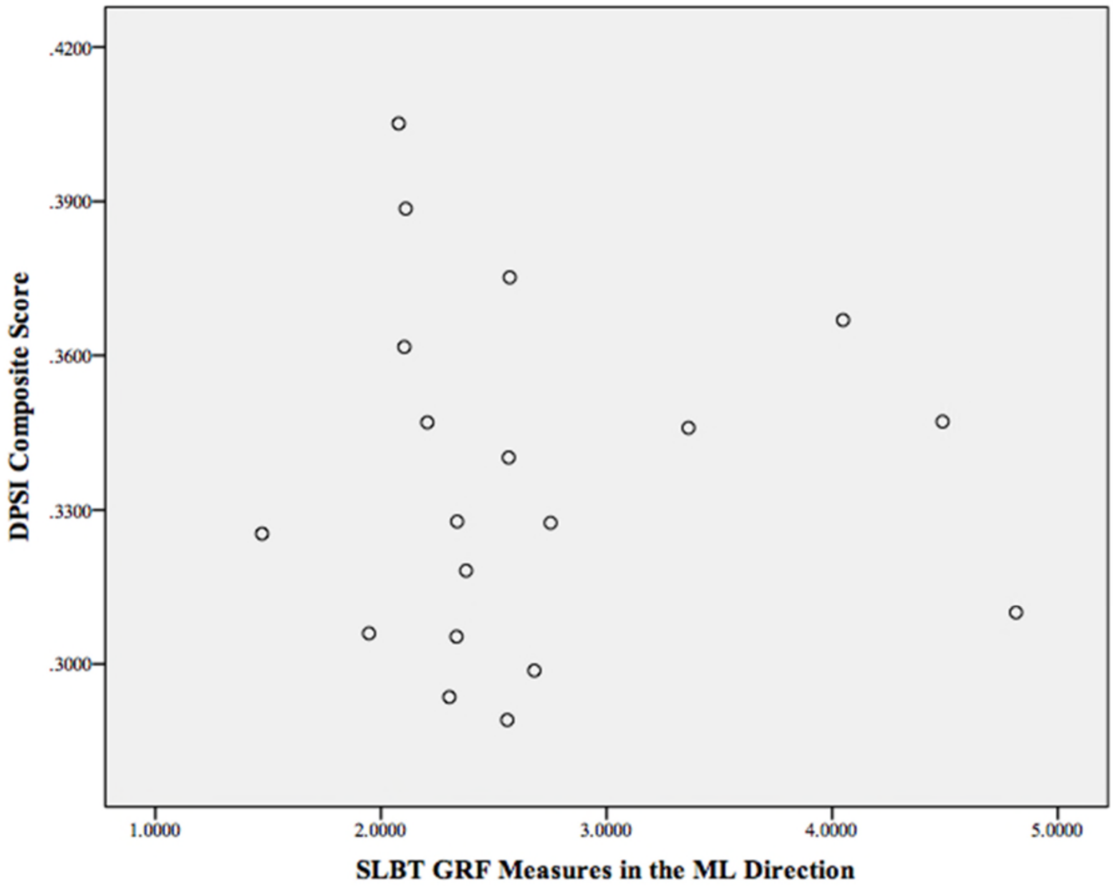

Figure 4. SLBT GRF Measurements and DPSI Composite Scores

5.0 DISCUSSION

The purpose of this study was to determine if there was a relationship among different tasks of postural stability, specifically different types of dynamic tasks of postural stability. Performances on a static balance task, a stable base of support reaching task, and a dynamic jump task were measured and utilized to establish if a significant correlation between these different types of postural stability tasks existed.

It was hypothesized that there would be no significant relationship between SEBT measurements and DPSI composite scores. This hypothesis was supported by the results of this study as there was no significant correlation found among any of the postural stability relationships. Furthermore, it was hypothesized that the relationship between the SLBT and SEBT measurements would be more strongly correlated than the relationship between the SLBT measures and DPSI composite scores. This hypothesis was not supported by the results of this study as there was no significant difference when comparing the two correlations.

5.1 RELATIONSHIP BETWEEN POSTURAL STABILITY TASKS

5.1.1 Relationship Between SEBT and DPSI Tasks

Dynamic postural stability was measured using two different types of assessments, a stable base of support task (SEBT) and a dynamic jump task (DPSI). The SEBT was modified in accordance to the protocol described by Gribble et al.[21] Composite scores were calculated from the MRD measurements in the anterior, posteromedial and posterolateral directions as described by Hertel et al.[24] The composite average, normalized MRD, of this sample was determined to be 83.12 ± 5.32%. The results of this sample were lower than those reported by Filipa et al.[11] (96.4 ± 11.7%, 96.9 ± 10.1%, 95.7 ± 5.2%, 97.4 ± 7.2%), and the results reported by Plisky et al (100.9 ± 8.4%).[45] This discrepancy may be due to the fact that the participants from these previous studies were recruited from organized sports teams while the participants from this study were only self-reported as recreationally active. The aim of this study was to recruit healthy, physically active participants. Potential candidates were screened and selected if they self-reported a score of at least 5 on the Tegner Activity Scale.[63] This criterion determined that participants were recreationally active, but perhaps a more active population would have yielded different results. A previous study found that female gymnasts demonstrate improved proprioception relative to healthy controls.[33] Both proprioception and postural stability are both maintained by the sensorimotor system, therefore a more athletic population may exhibit relatively improved postural stability due to a higher athletic ability and training. Since the results of the current study are similar to those previously reported, the results of this study could be considered an appropriate representation of SEBT performance in a recreationally active population.[21, 45]

Dynamic postural stability was also measured using the DPSI composite scores calculated during a single-leg jump task. Participants started 40% of their height away from the force plate, jumping over a 12-inch hurdle and onto the center of the force plate. GRF data were collected and analyzed in three directional planes and were used to calculate a DPSI composite score. The mean DPSI composite score in this study was determined to be 0.336 ± 0.033. These results are very similar to those reported by studies utilizing the same protocol for an anterior-posterior single leg jump task. Sell et al[56, 58] reported a mean value of 0.348 ± 0.035, and in a later study reported a mean value of 0.324 ± 0.041. The participants in the studies performed by Sell et al[56, 58] fit a more similar criterion for physically active than those from the SEBT studies.[56, 58] Since the DPSI composite scores of this sample are similar to previously reported results the results of the current study are appropriate representations of DPSI composite scores.

It was hypothesized that performance on the two dynamic postural stability tasks would be unrelated. The SEBT was considered more of a static task because the base of support remained stable while the participant reached in one of the prescribed directions. Conversely, DPSI was considered more of a true dynamic task because it required a jump-landing task and a quick establishment of a base of support. Correlational analysis between these two tests supported this hypothesis and revealed that there was no significant relationship between the SEBT measurements and DPSI composite scores ($r = 0.145$, $p = 0.554$). The findings of this study are in partial agreement with previous studies that have examined the relationship between different types of dynamic postural stability tasks.[41, 51] Nakagawa et al[41] found a weak relationship between the SEBT and a lateral step task. The results of this study are not in agreement with this finding. This may be due to the fact that a lateral step task is not testing the same aspects of postural stability as a jump-landing task, such as the one used in DPSI.

However, the findings from this study are in agreement with those found by Riemann et al.[51] This study found that there was no significant relationship between the SEBT and Single Leg Hop Test (SLHT) landing score. The SLHT is measured using landing and balance error scores. The number of errors during the landing of the jump-landing task are counted and used as the landing score variable, while the subsequent balancing following the landing are counted and used as the balance score variable. A higher score indicates worse postural stability. While the SLHT provides subjective measures and DPSI calculates objective measures, the agreement among results is likely due to the fact that both the SLHT and DPSI are measured using a similar jump-landing task.

The results of these analyses reinforce the theory that different types of postural stability tasks may utilize different strategies to maintain postural equilibrium. While both the SEBT and DPSI jump task are considered more dynamic than a task that involves no perturbation, such as the SLBT, these results demonstrate that even two dynamic tasks may be evaluating different components of postural stability. Future studies utilizing postural stability as a risk factor for injury should take a multi-faceted approach in measuring dynamic postural stability by using different types of dynamic tests to achieve a more comprehensive depiction of postural stability. Furthermore, while many clinicians already implement different dynamic tasks as part of the treatment and rehabilitation of athletes, these findings further validate the utilization of different types of postural stability exercises.

5.1.2 Relationship Between SLBT and Dynamic Tasks

Static balance was measured utilizing a Single Leg Balance Test (SLBT) with the eyes open. The protocol utilized was based on methodology described by Goldie et al.[14] We chose to allow participants to keep their eyes open during this test because visual input was allowed in both of the other dynamic postural stability tasks. Results of the SLBT were measured as the standard deviation of GRF data in the ML direction, and determined to be 2.69 ± 0.88. These findings are in agreement with those reported by Sell et al[56] (2.028 ± 0.651) using the same eyes-open protocol in healthy, physically active adults. They found that these procedures demonstrated extremely good reliability (ICC = 0.86). Since the outcomes of both studies are similar, the findings from the current study should be considered an appropriate representation of SLBT measurements.

Both the relationship between the SLBT and SEBT ($r = 0.359$, $p = 0.132$) and the relationship between SLBT and DPSI ($r = -0.015$, $p = 0.95$) were found to be not significant. These findings are in agreement with previous studies.[51, 56] Riemann et al[51] found no significant relationship between SLBT and SEBT performance.[51] Similarly, Sell et al[56] found no significant relationship between SLBT measures and DPSI scores.[56] The results from the current study are not consistent with the findings of Nakagawa et al[41] and Clark et al[7]. Nakagawa et al[41] found a very weak, but still significant, relationship between the SLBT measured with COP variables and performance on the SEBT ($r = 0.05$). Clark et al[7] measured the SLBT as either pass or fail trials, not utilizing any continuous data variables.[7, 64] Similar to Nakagawa et al[41], this study found a weak, but significant, relationship between the SLBT and performance on the SEBT ($r = 0.025$).[7] The discrepancy between these two studies and the current study is most likely due to the differences in the variables measured for static balance. It has been determined that force measures in the ML direction are the most sensitive and valid measures of static balance.[14] The studies by Nakagawa et al. and Clark et al. utilized COP and clinical measures, respectively.

Williams' test was used to compare the correlation coefficients between the SLBT and SEBT and the SLBT and DPSI. The results of this calculation found that the two correlations were not significantly different ($t = 1.216$, $p = 0.241$). Since neither dynamic task demonstrated a statistically significant relationship to a static postural stability task, it should not be surprising that Williams' test would also yield a non-significant result. It was hypothesized that the SEBT would be more strongly correlated to the SLBT compared to DPSI due to the nature of the task. The SEBT requires a stable, unmoving base of support, while the DPSI measures are derived from data collected during a jump task. The hypothesis for the secondary aim of this study was not supported by these results. It cannot be concluded by the results of the current study that different tasks of postural stability fall onto a continuum of challenge placed on the sensorimotor system. However, these results suggest that different dynamic tasks may be evaluating different aspects of the sensorimotor system, or different strategies for maintaining postural equilibrium.

5.2 THE SENSORIMOTOR SYSTEM AND POSTURAL STABILITY

The process of maintaining postural equilibrium requires the mechanoreceptors of the sensorimotor system to provide efferent information to the spinal cord and brain stem so the CNS can then organize the incoming sensory information, determine the timing, direction and amplitude of the corrective actions necessary to maintain postural equilibrium, and coordinate the appropriate motor responses.[49] Furthermore, this process requires both feedback and feedforward controls of the sensorimotor system.[50] Previous research has demonstrated that there is no relationship between static and dynamic tasks of postural stability, suggesting that dynamic tasks are more challenging to maintain postural equilibrium compared to a static task. However, the results of the current study demonstrate that there is also no relationship between two different tasks of dynamic postural stability.

These findings suggest that the efferent information transmitted to the CNS may be collected from different sensorimotor organs, or different sensorimotor organs may contribute in different capacities during the different dynamic tasks. The slower adapting mechanoreceptors may play a more prevalent role in a slow, preplanned dynamic task such as the SEBT. Conversely, a fast adapting, low threshold mechanoreceptor may contribute more during a functional, dynamic task, such as the jump task involved during DPSI. This would explain the lack of relationship found between the two different types of tasks. However, it should not be concluded by these results that postural stability tasks fall onto a continuum of challenge placed on the sensorimotor system. There was no significant difference found when comparing the relationship between the static balance task with the SEBT and the static balance task with DPSI. If the relationship between the SLBT and SEBT was determined to be significantly stronger than the relationship between the SLBT and DPSI, it could be suggested that the SEBT is more similar to a static balance task, and therefore, and easier task relative to a jump task. Since the findings of the current study did not demonstrate a significant difference between correlations, it can only be suggested that the two dynamic tasks evaluate different aspects of postural stability, rather than challenging the sensorimotor system in different capacities.

5.3 LIMITATIONS

This study has several limitations. Human error is always a risk when utilizing a clinical assessment tool. Unlike the SLBT and DPSI measures, the SEBT requires the researcher to mark at the furthest point of the reach. If the participant touches down quickly, it could be argued that the researcher not be able to mark the furthest reach point with 100% certainty. However, a study by Bastien et al found that visual estimation of the reach distance was valid when compared to the gold standard of a 3D motion analysis system (adjusted $R^2 = 0.98$, $p > 0.001$), reporting excellent reliability (ICC = 0.991).[3] Furthermore, this limitation was considered prior to testing, and every effort was made to reduce the potential source of error as much as possible by utilizing two researchers to assist with marking the reach distance.

An additional limitation of this study could be the limited directional data that was collected during the SEBT. Previous research has indicated that the three directions measured in this study for the SEBT protocol are representative of overall SEBT performance.[21, 44] However, the GRF data collected during the DPSI task is isolated in the anterior-posterior (AP), medial-lateral (ML) and vertical planes. It could be beneficial, if comparing directional data in the future, to have included SEBT directions that isolate measurements in just the ML plane by performing the task in the medial and lateral directions.

Lastly, the current study did not take the performance during failed trials into consideration. For both the SEBT and DPSI protocols, after a trial is deemed a failure, it is recollected with a successful trial. The procedure for the SLBT does not eliminate trials if the individual loses balance and steps down with the non-stance leg. Both the SEBT and DPSI consider a step down a failed attempt. While this protocol is consistent with previous research, it may be argued that an individual with diminished postural control would have more failed trials and that the data from successful trials may not differ significantly from that of an individual who displays increased postural control. It could be that the strategies involved in maintaining postural equilibrium during a successful trial differ from the strategies utilized during a failed trial. Postural stability may be able to be more comprehensively measured during the dynamic tasks if failed trials were considered and incorporated in the analysis of this data. However, the purpose of this study was not to develop a protocol that included the data from failed trials but rather utilize current and reliable protocols to assess postural stability.

5.4 STUDY SIGNIFICANCE

This is the first study to examine the relationship between a clinical dynamic postural stability measure (SEBT) and a force plate dynamic postural stability measure (DPSI). Furthermore, this study continues to suggest that different postural stability assessments may be challenging different components of the sensorimotor system or in different ways. The results of this study indicate that dynamic tasks with a stable base of support may not be assessing the same aspects of postural control as dynamic tasks requiring a jump and landing. Also, when the relationship between the SLBT and SEBT was compared to the relationship between the SLBT and DPSI, no significant difference was found. While the SEBT and DPSI certainly lack a linear relationship, it still cannot be determined if one test is a more challenging test of postural control or if they are just different tests of postural control. This study provides more insight into maintaining balance and postural equilibrium, and should assist in injury prevention research in the future.

5.5 FUTURE DIRECTIONS

This study provides more insight into postural stability measurements and their lack of relationship. This study used composite scores for both dynamic tasks and found that the two were not related. However, MRD was measured in three directions, and similarly, SLBT and DPSI GRF data were collected in three directional planes. While composite measurements were not related, perhaps a significant relationship could be found when examining variables in the same direction. This could potentially indicate that the strategies used to maintain postural equilibrium may be more similar when compared within a specific plane or direction. There is also a medial-lateral (ML) jump task that has been utilized in measuring DSPI that could be utilized in a future study.[56] Furthermore, this study could be replicated while collecting force plate data during the SEBT so that common variables, such as $GRF_{ML}SD$, could be compared among all tests.

Future research should examine the muscle activation patterns and biomechanical data during each of the dynamic tasks as well to determine if similarities exist. Electromyography (EMG) and kinematic data has been well established while performing the SEBT.[9, 19, 20, 22] Since the results of this study found that the SEBT and DPSI jump task were unrelated, EMG and biomechanical data would provide more insight into the differences in muscle activation and kinematic patterns involved in maintaining equilibrium during different types of dynamic tasks.

This study aimed to compare different types of dynamic tasks, one with a stable base of support and the other utilizing a jump task. There are clinical methods of measuring dynamic postural stability with a jump task, such as the Single Leg Hop Test.[51] Because DPSI can be measured almost exclusively in a laboratory setting, or at minimum in a clinic fitted with a free-standing force plate, it would be beneficial to find a clinical method of testing a similar type of dynamic task that is related to the gold standard. Riemann et al[51] found that performance on the SEBT and performance on the SLHT were not significantly related. This is in agreement with the current study that found the base of support task and jump task were also not correlated. Comparing a clinical jump task and a laboratory jump task may yield a significant relationship.

5.6 CONCLUSIONS

This study found that different types of dynamic postural stability are not related, and further supported the concept that static and dynamic postural stability measures are not related. While it is still unclear if different types of dynamic postural stability tasks vary in difficulty, these results provided more insight into the how the sensorimotor system may function differently in maintaining postural equilibrium during the varying tasks. The outcomes of this study help to guide future research by supporting the use of a multifaceted approach when utilizing postural stability assessments as a predictor of injury or in neuromuscular training programs. Clinicians should continue to use a variety of different types of balance tasks, including balance tasks that maintain a base of support and balance tasks that require a jump task, in order to measure and improve multiple aspects of postural stability.

APPENDIX A

TEGNER ACTIVITY SCALE

Level 10	Competitive sports- soccer, football, rugby (national elite)
Level 9	Competitive sports- soccer, football, rugby (lower divisions), ice hockey, wrestling, gymnastics, basketball
Level 8	Competitive sports- racquetball or bandy, squash or badminton, track and field athletics (jumping, etc.), down-hill skiing
Level 7	Competitive sports- tennis, running, motorcars speedway, handball Recreational sports- soccer, football, rugby, bandy, ice hockey, basketball, squash, racquetball, running
Level 6	Recreational sports- tennis and badminton, handball, racquetball, down-hill skiing, jogging at least 5 times per week
Level 5	Work- heavy labor (construction, etc.) Competitive sports- cycling, cross-country skiing, Recreational sports- jogging on uneven ground at least twice weekly
Level 4	Work- moderately heavy labor (e.g. truck driving, etc.)
Level 3	Work- light labor (nursing, etc.)
Level 2	Work- light labor Walking on uneven ground possible, but impossible to back pack or hike
Level 1	Work- sedentary (secretarial, etc.)
Level 0	Sick leave or disability pension because of knee problems

Figure 5. Tegner Activity Scale[63]

APPENDIX B

ADDITIONAL TABLES AND DESCRIPTIVE BOXPLOTS

B.1 INDIVIDUAL RESULTS

B.1.1 Demographic Information

Table 5. Individual Demographic Information

Subject ID	Age (years)	Height (cm)	Weight (kg)	Sex	Leg Dom.	Leg Length (cm)
PS03	22	168	58.3	F	R	91
PS04	21	181.5	73.9	M	L	95
PS05	31	177	66.6	F	R	94
PS06	21	163.5	61.2	F	R	87
PS07	25	175.4	79.4	F	R	91
PS08	23	163.2	50.6	F	R	83.5
PS09	21	179.7	65.6	F	R	93.5
PS10	25	189	86.8	M	L	99
PS11	20	186	83.6	M	R	94
PS12	23	163	54	F	R	85
PS13	20	175	71.5	M	R	96
PS14	20	181	78.4	M	R	96
PS15	21	166.6	75.4	F	R	86
PS16	21	179.6	71.6	M	R	92.5
PS17	22	194	119.6	M	L	100
PS18	22	164	64.4	F	R	86.5
PS19	21	166.6	78.3	F	R	88
PS20	21	156.1	64.5	F	L	83
PS21	21		65.8	F	R	93.5

Leg Dom = Leg Dominance defined as leg preferred to kick a ball
Leg Length = Dominant Leg Length

B.1.2 Force Plate Postural Stability Tasks

Table 6. Individual Force Plate Measures of Postural Stability

Subject ID	SLBT	DPSI
PS03	1.4731	0.3254
PS04	2.5708	0.3752
PS05	2.0787	0.4051
PS06	2.6802	0.2987
PS07	4.8149	0.31
PS08	2.3773	0.3182
PS09	2.7520	0.3275
PS10	2.3377	0.3278
PS11	3.3633	0.3459
PS12	2.2057	0.347
PS13	4.4895	0.3472
PS14	2.1101	0.3886
PS15	2.3351	0.3053
PS16	2.5662	0.3402
PS17	4.0483	0.3668
PS18	2.3033	0.2936
PS19	2.5602	0.2891
PS20	1.9472	0.306
PS21	2.1036	0.3616

SLBT = Average SD of GRF data in ML direction across 3 trials
DPSI = Average composite score across 5 trials

B.1.3 Star Excursion Balance Test Performance

Table 7. Individual Star Excursion Balance Test Maximum Reach Distances

Subject	Leg Length (cm)	A (cm)	PM (cm)	PL (cm)
PS03	91	73.83	67	54.5
PS04	95	88.67	81	77.5
PS05	94	88.83	79.67	67.67
PS06	87	70.3	69.6	67.13
PS07	91	80.5	78.17	66.9
PS08	83.5	81.33	79.17	65.5
PS09	93.5	91.33	73.83	66.33
PS10	99	92.5	84	83
PS11	94	95.83	83.17	73.33
PS12	85	71.17	66.17	56
PS13	96	89.17	88.67	74.83
PS14	96	84.83	79.17	64.33
PS15	86	82	76.33	70.67
PS16	92.5	84.17	78.17	59.5
PS17	100	91.67	89.5	81.83
PS18	86.5	77	71.83	63.17
PS19	88	82	63.07	51.83
PS20	83	76.5	71.78	67
PS21	93.5	80.17	83	73

A = Average anterior maximum reach distance across 3 trials
PM = Average posteromedial maximum reach distance across 3 trials
PL = Average posterolateral maximum reach distance across 3 trials

Table 8. Individual Star Excursion Balance Test Normalized MRD Measurements

Subject	A (%)	PM (%)	PL (%)	Comp. (%)
PS03	81.14	73.63	59.89	71.55
PS04	93.33	85.26	81.58	86.73
PS05	94.5	84.75	70.92	83.39
PS06	80.8	80	77.16	79.32
PS07	88.46	85.9	73.52	82.63
PS08	97.41	94.81	78.44	90.22
PS09	97.68	78.97	70.94	82.53
PS10	93.43	84.85	83.84	87.37
PS11	101.95	88.48	78.01	89.48
PS12	83.73	77.84	65.88	75.82
PS13	92.88	92.36	77.95	87.73
PS14	88.37	82.47	67.01	79.28
PS15	95.35	88.76	82.17	88.76
PS16	90.99	84.5	64.32	79.94
PS17	91.67	89.5	81.83	87.67
PS18	89.02	83.04	73.03	81.7
PS19	93.18	71.67	58.9	74.58
PS20	92.17	86.35	80.72	86.41
PS21	85.74	88.77	78.07	84.19

A = Average, normalized MRD in anterior direction across 3 trials
PM = Average, normalized MRD in posteromedial direction across 3 trials
PL = Average, normalized MRD in posterolateral direction across 3 trials
Comp. = Average, composite, normalized MRD across 3 trials

B.2 DPSI DIRECTIONAL DATA

Table 9. Directional Stability Descriptive Data

	Mean		SD	Median	LQ	UQ
MLSI	0.1389	±	0.0093	0.1428	0.1325	0.1447
APSI	0.0278	±	0.0060	0.0262	0.0240	0.0319
VSI	0.3039	±	0.0347	0.2989	0.2730	0.3319

SD = Standard Deviation
LQ = Lower Quartile
UQ = Upper Quartile

Table 10. Individual Directional Stability Indices

	MLSI	APSI	VSI
PS03	0.1446	0.0283	0.2900
PS04	0.1437	0.0241	0.3457
PS05	0.1428	0.0253	0.3781
PS06	0.1202	0.0261	0.2720
PS07	0.1407	0.0409	0.2730
PS08	0.1430	0.0391	0.2812
PS09	0.1356	0.0255	0.2968
PS10	0.1325	0.0198	0.2989
PS11	0.1483	0.0206	0.3117
PS12	0.1456	0.0319	0.3132
PS13	0.1489	0.0271	0.3122
PS14	0.1317	0.0337	0.3639
PS15	0.1339	0.0264	0.2730
PS16	0.1447	0.0198	0.3072
PS17	0.1429	0.0333	0.3359
PS18	0.1219	0.0240	0.2658
PS19	0.1250	0.0230	0.2596
PS20	0.1537	0.0263	0.2631
PS21	0.1400	0.0311	0.3319

MLSI = Stability Index calculated in the Medial-Lateral plane
APSI = Stability Index calculated in the Anterior-Posterior plane
VSI = Stability Index calculated in the vertical plane

B.3 DESCRIPTIVE DATA PLOTS

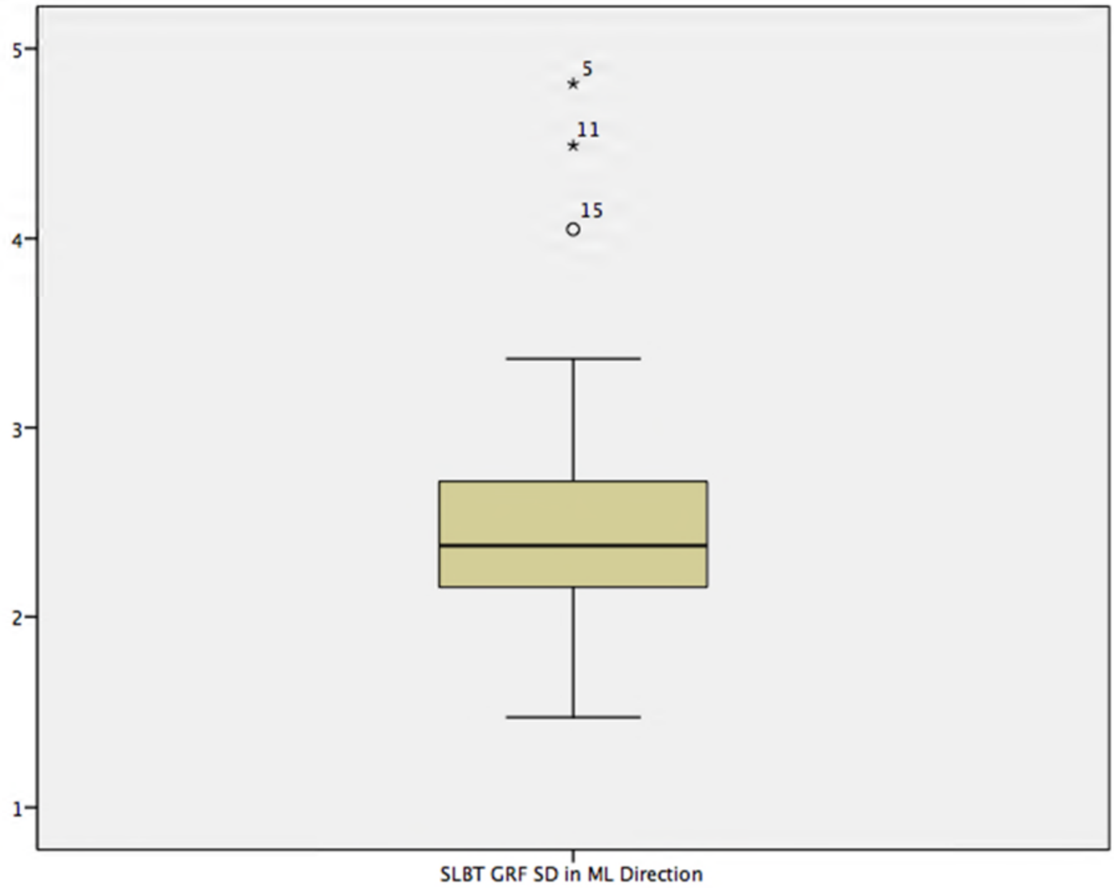

Figure 6. SLBT Box Plot

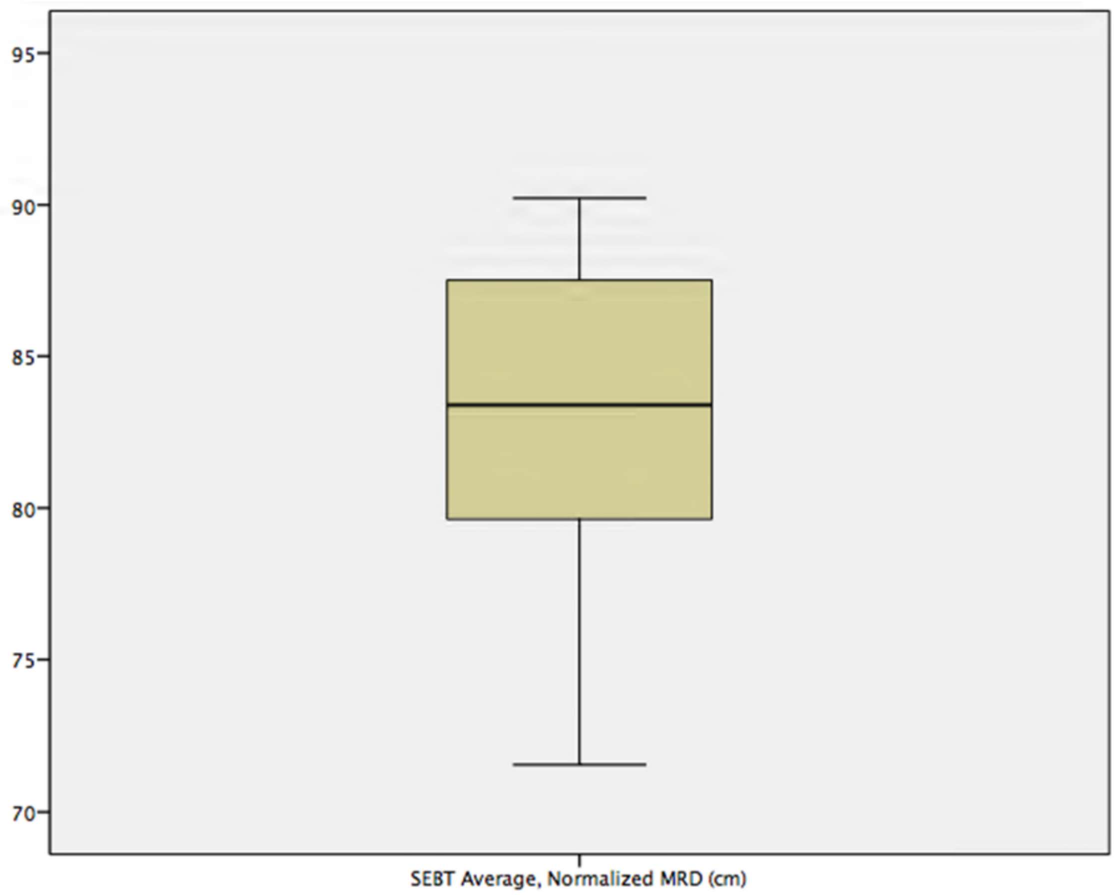

Figure 7. SEBT Box Plot

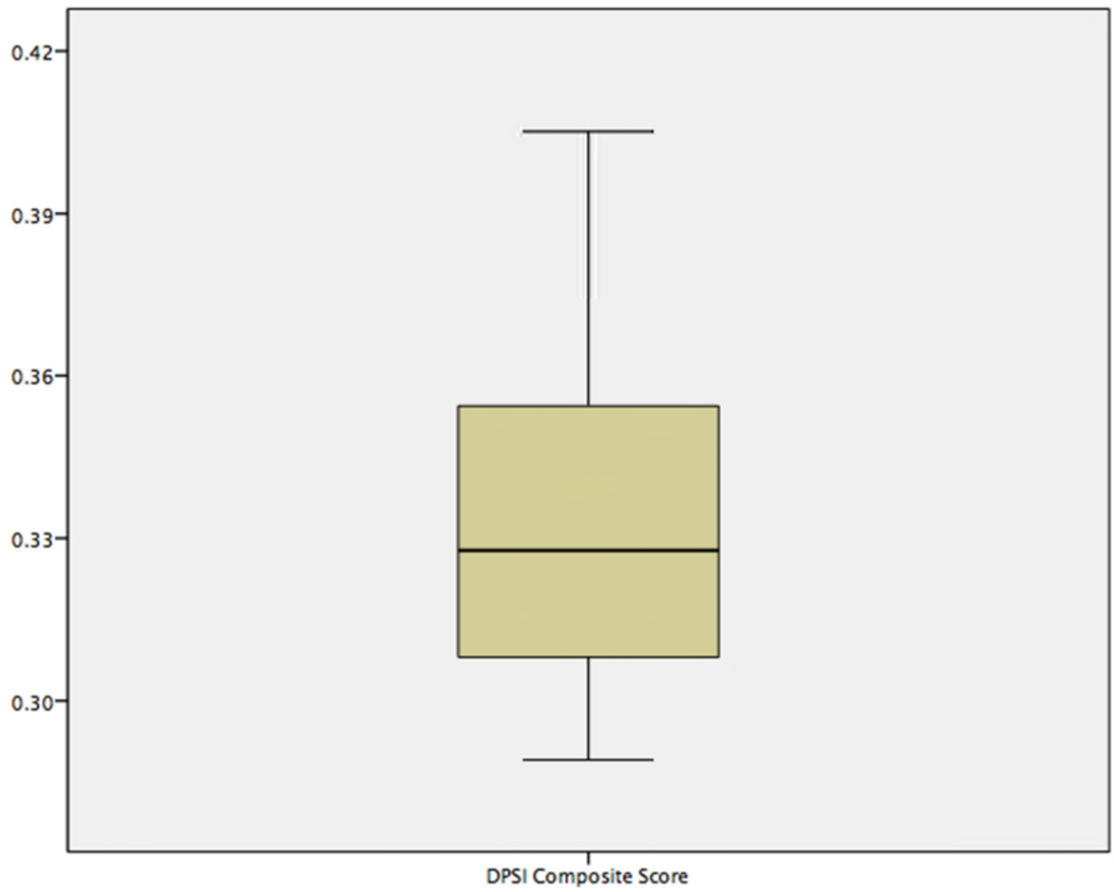

Figure 8. DPSI Box Plot

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