COMPARISON OF A SMARTPHONE BALANCE TEST AND COMMONLY USED BALANCE MEASURES

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ABSTRACT

David Mincberg: Comparison of a Smartphone Balance Test and Commonly Used Balance Measures
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Balance is a complex process that is a component of concussion evaluation and treatment. **Purpose:** To compare balance measures obtained from Sway Balance Test (SBT), a smartphone-based test, to common force plate measures and sternal position data, as well as to determine the reliability of the SBT. **Methods:** 24 college-aged participants completed two testing sessions. During each session participants completed three Sway Balance Tests while force plate and sternal position data were recorded. Participants also completed the Sensory Organization Test. **Results:** SBT overall scores were strongly inversely correlated with center of pressure elliptical sway area (r=-0.816, p<0.001), sway speed (r=-0.888, p<0.001), and sternal position marker elliptical sway area (r=-0.899, p=0.001). It was weakly correlated with the SOT (r=0.420, p=0.041). The SBT had a high test-retest reliability of 0.942.

Conclusions: Our results indicate that the SBT is concurrently valid and reliable for measuring balance in healthy college aged individuals.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

BBS Berg Balance Scale

BESS Balance Error Scoring System

COG Center of gravity

COM Center of mass

COP Center of pressure

ESA Elliptical sway area

FP Force plate

SBT Sway Balance Test

SEBT Star Excursion Balance Test

SOT Sensory Organization Test

SPM Sternal position marker

SS Sway speed

TUG Timed Up and Go Test

CHAPTER I

INTRODUCTION

Balance is often defined as the ability to maintain the center of mass of the body within the base of support with minimal accessory movement.[1] This is vital to activities of daily living.[1] Maintaining balance is a complex process that relies on input from many sources. Visual information is used to determine body position and orientation relative to surroundings and any upcoming obstacles. Vestibular information is obtained from the inner ear regarding acceleration and rotation of the head, as well as orientation relative to gravity. Finally, proprioceptive information from mechanoreceptors in soft tissue provide input on body position and pressure.[2] These inputs are used to create motor output, which keeps the body stable and upright. This process is largely involuntary, but at times may include voluntary actions to correct an error.[3]

There are many situations in which balance may become disrupted or impaired. As age increases, balance decreases,[4,5] which may contribute to the increased rate of falls in older adults.[6] Balance also decreases with muscular fatigue,[7] although this effect is not long lasting and returns to baseline after a short rest period.[8] Various lower extremity musculoskeletal injuries may also affect balance. A deficit in balance can be seen immediately after musculoskeletal injury and may last for several years.[9,10] Recently research has focused on balance after traumatic brain injury, specifically concussion. These studies have found there is often a decrease in balance seen immediately post-injury, which can last for several days.[11-13] For this reason, many clinical practice guidelines recommend using balance testing during concussion evaluation and follow-up testing.[14,15]

While many methods exist to quantify balance, they vary widely in their intended use, validity, and reliability. Objective measures can be obtained from force plates on which the participant attempts to maintain their balance, or from accelerometers applied to various points on the body.[3,16] However, these methods are often costly and produce a large amount of raw data which is not immediately useful to the clinician.[17] Thus, these measures are not feasible for use in most clinical settings. Many sports medicine and therapy practice guidelines recommend the use of balance scoring systems to measure deficits post-injury. While these clinical tests are easy to perform and affordable, there are several important drawbacks. These include decreased sensitivity, subjective "balance quality" measures, and scores that may be difficult to compare over time.[14,18] An example of this type of task is the Balance Error Scoring System (BESS). The BESS consists of three different positions held for 20 seconds each on both a stable and unstable surface. While this test has been shown to have moderate to good reliability,[18] it is not without limitations. The BESS scoring system relies on "errors" which include the participant losing their balance or touching a foot on the ground. Several studies have found large variance in the amount of errors detected during the test.[19-21] Previous research has demonstrated the BESS has an intra-rater reliability ranging from 0.50 to 0.88 and inter-rater reliability ranging from 0.44 to 0.83.[21] The more simple BESS test conditions (feet together, firm surface) commonly result in very few errors, leading to low utility in healthy individuals as well as a relatively low reliability.[21] In contrast, the more difficult portions of the test are better able to differentiate between those with balance deficits and those without, as well as having a higher reliability.[18,21] The BESS also requires examiners to be fully trained in the administration of the scoring system to elicit good inter-rater and intra-rater reliability.[21] While the BESS is a good clinical tool, more sensitive and objective balance assessment tests, specifically tests that do not rely on human judgment, may improve patient care.

Accelerometers encompassed in many smartphones have the potential to be feasible balance assessment tools and allow for objective data collection. Smartphone applications that utilize the features of the accelerometer are widely available and relatively cheap resulting in extremely portable and accessible accelerometer devices.[22] The output measured from these smartphone accelerometers has been found to be valid and reliable in measuring standing balance compared to laboratory measures.[23,24]

The Sway Balance Test (SBT) (SWAY Medical, Tulsa, OK, USA), which is currently available for purchase, is a mobile balance test that has been approved by the United States Food and Drug Administration. This test uses the accelerometers in compatible smartphones to quantify balance using a custom protocol. The results of this test, as well as reported concussion symptoms and results of an included reaction time test are stored on Sway Medical's Health Insurance Portability and Accountability Act compliant online database. The application instructs the participant to hold the phone to their chest while completing a modified version of the three positions used in the BESS. As opposed to completing these positions on an unstable surface, the Sway Balance Test instructs users to complete the single leg and tandem stances on the dominant and non-dominant sides, resulting in five total test positions on a stable surface. Unlike the BESS, each trial is 10 seconds. From these data the application gives the clinician a 0-100 "balance score"; where a higher score indicates better overall balance. One pilot study compared results from the Sway Balance application to scores on the Biodex Balance System SD (Biodex Medical Systems, Shirley, NY, USA).[24] While the results from this research showed a moderate correlation between the two devices, it utilized a developmental version of the Sway

Balance software, which only measured anterior and posterior movement. A second study aimed to compare Sway Balance results to scores obtained from the BESS.[25] This study found that individuals with low BESS scores tended to have high Sway Balance Scores, but it did not investigate any other variables. At this time there is no research available that investigates the relationship between the current, commercially available version of the Sway Balance application and commonly accepted force plate measures such as sway speed and elliptical sway area, general center of mass measurements, or more specific clinical tests such as the Sensory Organization Test.

Therefore, the purpose of this study was to examine if scores obtained from the Sway Balance Test correlate with traditional center of pressure, center of mass, and clinical measures of balance in healthy recreationally active college students. We also investigated how the reliability of the Sway Balance Test compares to traditional laboratory measures of balance. The following research questions guided the current study.

Research Questions

Research Question 1: Do Sway Balance Test scores correlate with traditional force plate measures of balance, sternal position marker measurements, and clinical balance measures in healthy, recreationally active college students?

Research Question 2: Will the reliability of traditional force plate balance measures and sternal position marker balance measures be higher than that of the Sway Balance test?

Research Hypotheses

Research Hypothesis 1: The Sway Balance Test total score will be: moderately inversely correlated with traditional force plate measures of balance (sway speed, elliptical sway area, excursion), strongly inversely correlated with balance measures obtained from a sternal position marker (sway speed, elliptical sway area, excursion), and moderately positively correlated with SOT composite equilibrium score.

Research Hypothesis 2: The Sway Balance Test total score will have a lower reliability than that of the traditional force plate and sternal position marker balance measures.

Clinical Significance

There are currently several smartphone accelerometer applications available for purchase that could potentially be used as tools to measure balance. The Sway Balance Test, which has also received FDA approval as a medical device, is currently being marketed to athletic trainers and other health care providers for the purpose of concussion evaluation and management. While the developers of this test state that it is able to accurately measure balance, there is little research available to substantiate these claims. Much of the current research compares these applications to clinical measures such as the BESS, or uses incomplete developmental versions of the currently available applications. If a strong correlation is found between the Sway Balance Test and traditional force plate measures, it could further validate a potentially affordable and simple to administer test of balance. This could provide a tool for health care providers that uses objective data to quantify the balance of their patients.

CHAPTER II

LITERATURE REVIEW

Introduction

Balance is a complex process that utilizes many body systems to maintain an upright posture both with and without the presence of perturbations.[2] This is necessary for both activities of daily life and success in sports and athletics.[2] Due to the multiplanar nature of balance, the most accurate methods of quantifying balance require expensive and data intensive tools to measure movement in three dimensions. Because of restraints such as time consuming operator training and high cost, these tools are not accessible to many clinicians. Many clinical balance assessment tools rely on subjective measures to quantify when a participant "loses" their balance, and therefore do not provide a "quality of balance" measurement.[18] While accelerometers have long been used in balance and posture research,[16,22,26,27] they have recently become more affordable and accessible due to the popularity of smartphones. These accelerometers have been proven valid and reliable when raw data is exported and traditional methods are used to calculate acceleration.[28] The Sway Balance Test is a smartphone application that is marketed towards health care providers to quantify balance using these accelerometers. However, there has been little research to date regarding the validity or reliability of the Sway Balance Test.[24,25]

Balance processes

Balance has been defined in multiple ways from "the process of maintaining the center of gravity within the body's base of support"[3] to "a generic term describing the dynamics of body posture to prevent falling".[2] The body relies on three different sensory systems to maintain balance. The visual system is used primarily for orientation when the supporting surface is uneven or is providing unreliable input, such as when standing on a soft surface.[2] The vestibular system senses changes in orientation and acceleration of the head. When the head experiences acceleration the eyes reflexively move in the opposite direction. This is known as the vestibulo-occular reflex, which allows the eyes to maintain fixed on a single point during motion, allowing the visual system to provide accurate input.[29] Finally the somatosensory system is used to sense the location of the limbs relative to the rest of the body and to sense perturbations applied to the body.[2] The somatosensory system relies primarily on mechanoreceptors in muscles to detect changes in muscle tension.

Two main mechanoreceptors are muscle spindles and golgi tendon organs. Muscle spindles are located within muscles and detect changes in tension and muscle length. Golgi tendon organs are located in the musculotendinous junction and detect overall muscle tension. When muscles are lengthened, afferent signals from these mechanoreceptors are sent from peripheral nerves to the central nervous system. Input from plantar mechanoreceptors in the soles of the feet is also used in maintaining balance. These sensors determine the amount of pressure on various parts of the foot, and are utilized during quiet standing when the stretch reflex is not utilized as often.[30] If a muscle is lengthened, the mechanoreceptors will send a single to the central nervous system which will then send efferent signals back to the muscles without conscious processing. This efferent signal causes a reflexive contraction of the muscle known as the stretch reflex.[29] Muscle contractions then cause joint movement to correct for the perturbations experienced. All three of these systems work in combination to provide constant feedback on the positioning of individual limbs, the orientation of separate body parts to each other, and the body's relationship to its surrounding environment. By continuously reacting to these afferent signals with low-level reflexive muscle contractions the body is able to maintain balance during quiet standing.[29]

Factors leading to balance deficits

As discussed earlier there are several systems that must work together properly for the body to maintain balance. Changes in any of these systems may cause balance to suffer. The cause of the changes can range from somatosensory deficits following acute musculoskeletal injury to changes in information processing after a traumatic brain injury. [3,10,12,31,32]

Aging

There is much concern over the rate of falls in the elderly. It has been estimated that between 32 and 49 percent of adults over the age of 72 will experience a serious fall in any given year.[33,34] While there is often not one specific cause, it has been demonstrated that postural control decreases with age during both standing and walking.[4,5,35,36] One possible contributing factor found by Cofré Lizama and colleagues is a decreased reaction time in older individuals. It was found that reaction time to an external stimulus and the ability to effectively shift the center of mass in response to this stimulus were decreased in those over the age of 72.[5] Several studies have shown that scores on the Berg Balance Scale (BBS), Balance Error Scoring System (BESS), and Timed Up and Go (TUG) test worsen with age.[35,37,38] While these changes may not be dramatic, Downs and colleagues found that there was a much larger variability in balance scores over the age of 70.[37] As there is a gradual decline of balance abilities in older individuals, many clinical tests, which rely on "errors" or a time to complete a task, may not accurately detect subtle changes in balance, which occur over time. These tests may also not be accurate for use in older patients due to the wide range of balance abilities seen. While one individual may need a more challenging test such as the BESS to detect errors, others may demonstrate deficits with a less taxing test such as the TUG. This wide range of balance ability supports the need for an accurate and affordable balance test for the screening of older patients, which can be used across all ability levels.

Fatigue

There are two broad types of fatigue experienced during physical activity. The first of these is local muscle fatigue, which is due to a decrease in substrates such as adenosine triphosphate (ATP), creatine phosphate (CP), and glycogen which are needed for muscles to function correctly.[39] Most research shows both ATP and CP will return to baseline values within one to three minutes.[39] The second type of fatigue is central fatigue. This occurs when there is a decrease in central nervous system stimuli being sent to muscles.[39] This leads to a decrease in both contraction velocity and maximum force production.[39] Both central and peripheral fatigue are seen following moderate to intense sport based physical activity.[39] Several studies have demonstrated that balance decreases following fatiguing exercise.[7,8,18,40] Wilkins and colleagues found that participants who completed a fatiguing protocol performed significantly worse on the BESS immediately after exercise.[7] This effect has also been demonstrated via force plates.[8] Two studies have attempted to determine the time needed following cessation of exercise for balance to return to baseline as measured by the BESS. Fox and colleagues[8] found that balance returned to baseline between eight and 13 minutes following exercise, while Susco and colleagues[40] found that this occurred within 20 minutes. Fox and colleagues investigated collegiate athletes while Susco and colleagues investigated recreationally active college students, whose lower conditioning level may have caused the slower recovery time. It has also been shown there is no difference in change in BESS scores between participants completing an aerobic exercise protocol and those completing an anaerobic exercise protocol as long as they reach a fatigued state.[8]

Musculoskeletal Injury

Musculoskeletal injuries are common occurrences in active individuals, which can lead to balance deficits. The majority of research to date has investigated the role of ankle sprains on standing balance.[9,10,32,41] These effects can be seen both acutely[10] and over many years.[9] Holder–Powell and Rutherford found that participants with mild to severe ankle and knee injuries demonstrated balance deficits several years after reporting a full resolution of symptoms related to their injury.[9] The duration and severity of the deficits were not related to the type or severity of injury that occurred, suggesting that balance deficits may not be due to the physical trauma of an injury. These deficits were traditionally thought to be due to nerve fiber damage and therefore a deafferentation of the joint, causing a loss of afferent input and proprioception.[42] Recent research has shown that balance may be decreased in both the injured and uninjured limb following an acute ankle sprain.[10,32] Doherty and colleagues found that these individuals had greater difference between eyes-open and eyes-closed balance than healthy participants.[10] This suggests a reorganization of input systems after injury with increased reliance on visual input. The long lasting and multifactorial effects of injury on balance requires accurate and objective testing for both successful return to sport and full recovery for activities of daily living.

Concussion

Concussions are “a traumatically induced transient disturbance of brain function and is caused by a complex pathophysiological process”.[15] This has been found to be a relatively common injury in competitive athletics. In a 2007 observational study of 100 high schools and

180 colleges, concussions accounted for 8.9% and 5.8% of all injuries respectively.[43] The sports with the highest rates of concussion were collision and contact sports, most notably football, ice hockey, and soccer.[31,44] Signs and symptoms can vary widely by case,[45] including a delayed onset of symptoms, with headache and dizziness most often reported in the literature.[15,46,47] Many studies have also found significant balance deficits as measured using the BESS, force plate analysis, or the Sensory Organization Test after a concussion.[12,13,48,49] These balance deficits commonly return to baseline as early as 1-3 days post-injury as measured using clinical tests such as the BESS or Sensory Organization Test,[11,12] but decreased balance ability can be detected with advanced force plate testing even after acute balance deficits return to baseline.[50] Because of this range in presentation of signs and symptoms, many medical organizations recommend using multiple assessment tools, including symptom tracking, neurocognitive testing, and an objective balance assessment.[15,46]

Balance Training

While there are many factors that can decrease balance over time, there have also been many studies, which suggest that balance ability can increase with training. Matsuda and colleagues have examined the balance abilities of soccer players in several studies. They determined that soccer players demonstrate lower sway velocity, medial lateral, and anterior posterior sway than not only non-athletes, but also athletes of a similar competitive level in swimming and basketball.[51,52] This suggests that those who spend a greater amount of time training on one leg may be able to develop greater balance. Conversely those who spend a large amount of time using both feet for support or in an environment that does not provide balance challenges will demonstrate decreased postural stability as measured using traditional force plate balance testing.[51,52] McLeod and colleagues also showed that it was possible to improve balance as demonstrated by BESS scores with a six week neuromuscular training program in high school females.[53] While that study used a supervised instruction type program, Emery and colleagues found that static and dynamic balance could both be improved with a simple at-home balance program using a wobble-board with the same age group.[54] This same training effect has also been demonstrated in elderly participants.[55] It is important to note that this training effect may not be permanent. A study investigating elite volleyball players found that force plate balance measures significantly decreased following a month without training.[56]

Because many factors may influence balance performance, it is important to be able to accurately measure postural sway and quantify any balance deficits that may exist. These measurements can be used to screen for fall risk, help evaluate for a traumatic brain injury, or guide return to play progressions following musculoskeletal injury.

Measuring Balance

Center of Pressure Measurements

Force plates have been an accepted method of quantifying balance for many years.[16] This is commonly done using center of pressure. Center of pressure is defined as the location of the vertical ground reaction force vectors.[2] In other words, center of pressure is the average of all pressures being transmitted from the feet into the ground. In the majority of balance research only one force plate is used, which results in a net center of pressure, which is the average pressure between the two feet. During single leg stance the same principle can be applied, with the center of pressure being the point under the stance foot where pressures from the heel and medial and lateral forefoot are centered. As with double leg stance this point will oscillate both medial/lateral and anterior/posterior as the participant attempts to maintain balance. It is important to note that center of pressure is a force plate measure, while center of gravity is a vertical projection of the center of mass onto the ground.

There are several variables that can be obtained by tracking the movement of a participant's center of mass over time. The most common of these include average sway speed, elliptical sway area, and path length. Elliptical sway area is found by plotting all locations of the center of pressure over a trial, then fitting an ellipse to this data that covers 95% of all data points. The area of this ellipse is then calculated, resulting in a single outcome variable. Path length is determined by calculating the total distance the center of pressure travels over the course of a trial. If path length is divided by the length of the trail, the average sway speed is the resulting variable. Nguyen and colleagues examined the usefulness of these three measures as well as several other commonly used processes.[57] It was found that there was not one data analysis process that was significantly more accurate than others. However, the authors concluded that an accurate balance assessment should include measures of area, such as elliptical sway area or range, and measures of speed.[57]

Center of Mass Measurements

Center of mass has been defined as the point at which the total body mass can be assumed to be concentrated.[58] In other words, it is the combination of masses of various body segments relative the their overall length. During standing balance, an individual attempts to control their center of mass in space. This is done by manipulating their center of pressure through ankle, knee, and hip movement.[58] Because of this, the center of pressure will tend to oscillate around the center of mass in normal standing as they attempt to maintain an upright posture. This idea allows for one simple method for estimating center of mass location. When all measureable horizontal forces are equal it can be assumed that the vertical projection of the center of mass is the same as the center of pressure.[58] A higher variability between center of mass and center of pressure would imply more uncontrolled motion of the body as the participant attempts to remain stable.[59] It is important to note that in many circumstances the center of mass and center of pressure may be moving in opposite directions. For example if a participant's center of mass is shifted anterior they will plantarflex at the ankle to correct this. This plantarflexion causes the center of pressure to move anteriorly as more pressure is placed on the front of the foot. At the same time this plantarflexion will cause their center of mass to drift posteriorly as they correct the previous shift.[58] Both methods have been found to be accurate measures of assessing balance, although as discussed earlier, they measure different factors. Center of mass measurement analyzes the actual movement of the estimated center of mass, while center of pressure effectively measures the body's attempts to control that movement. Over the course of a measurement trial, these two measurements will oscillate in both the frontal and sagittal planes, resulting in comparable values.[59]

As discussed earlier, center of mass can be thought of as the weighted average of the mass of each body segment. This is the basis for a mathematic process to calculate center of mass known as the kinematic model or segmental method.[10] This method relies on the idea that the body is made up of many rigid segments. Each of these segments will have its own center of mass and make up a percent of total body mass. By measuring the lengths of these segments it is possible to estimate the center of mass of the entire body. However this is a time consuming and equipment intensive method. At this time there are no normative data available correlating center of mass to a specific percentage of height for males and females of different body types. However, it has been stated that the center of gravity (in this case used interchangeably with center of mass) is located at approximately 57% of a person's height for males and 55% for females.[60]

While the segmental method is relatively easy to calculate with computer based models, it either requires a large amount of time to measure the length of body segments or the capability to use "markers" placed at various joints to electronically calculate the center of mass. As this method is not feasible for many clinicians, recent research has focused on the use of a single fixed point on the pelvis or torso to measure balance.[16,22,27,61-63] This research recognizes that these locations are not equal to the center of mass, but that a fixed point will move parallel to the path of the center of mass and may be adequate for measuring postural sway.[64] Several of these studies used a single accelerometer to measure gait as well as balance.[23,27,63] Moe-Nilssen advocated for the placement of an accelerometer over the L3 spinous process as it most effectively neutralizes motions of the upper and lower extremities which allows for a more accurate measure of true motion.[64] With this placement it is necessary to correct for the curvature of the back either through mechanical correction at the time of placement or through mathematical analysis post-testing. It was found that test-retest reliability for this placement varied greatly by test condition. While standing on both feet with eyes open the test recorded a relatively low reliability of 0.58.[27] However when the test was made more difficult by having the participant stand on one foot, the reliability improved to 0.85.[27]

A separate study used an accelerometer placed over L3 to investigate the correlation between accelerometry values and scores on various clinical balance tests. This study found a moderate to strong correlation (0.62-0.83) correlation with clinical balance tests including the Berg Balance Scale and the Timed Up and Go test.[63] This same study also found that an accelerometer placed over L3 was able to differentiate between those with a history of falls and those with no history of falling.

Several other locations have been suggested for single accelerometer placement. Brown and colleagues attempted to use accelerometers to predict errors on the Balance Error Scoring System. Accelerometers were placed on various points and an error was counted when the body part moved outside of a predetermined distance. This investigation found that this method had a correlation with manual BESS grading of 0.92.[17] This study also found that it was possible to use only one accelerometer on the forehead to detect BESS errors. This single-sensor setup had a correlation with manual BESS grading of 0.90.[17] Essentially, this suggests that the head reacts in a similar fashion to the rest of the body during the BESS stances.

Accelerometers positioned over the sternum have also been used in multiple studies.[16,61] It is important to note that this location is not an estimated center of mass measurement, but instead moves parallel to the center of mass with a similar magnitude.[62] This option may be attractive for clinicians as it allows for accurate and reliable placement due to the ease of palpating the sternum. Dalton and colleagues compared data from a single sternal accelerometer to a gait mat in participants with and without Huntington's disease. Strong agreement was found (ICC=0.95) between the two devices.[61] The accelerometer was also able to accurately differentiate between those with and without Huntington's disease during standing balance. A separate study compared sternal placement of an accelerometer to force plate data during several balance conditions (eyes open, eyes closed on firm surface, eyes open and eyes closed on foam surface) and found strong agreement of path length and mean velocity between center of pressure and center of mass.[16] This placement may be beneficial over L3 placement as it requires less correction for an accelerometer to be correctly aligned vertically and can allow for more accurate and consistent placement of the accelerometer.

Clinical Measures

There are two general types of clinical balance tests: dynamic and static. It is suggested that dynamic balance tasks are more related to athletic ability while static tasks do not have as much carryover to athletics.[65] Current evidence suggests that there is not a strong relationship between performance on static and dynamic tests.[65]

The Star Excursion Balance Test (SEBT) is an example of a commonly used dynamic clinical balance test. It consists of a grid from which lines extend at 45-degree angles. The participant stands in the center on one foot and reaches as far as possible in each direction with their non-weight-bearing foot. The distance from the center of the star to the distance reached is recorded. This process is repeated three times and an average is obtained. As the test relies on an objective distance measurement, the Star Excursion Balance Test has been shown to have a high intra-tester reliability of 0.78 to 0.96. Partly due to a sample design that did not account for a learning effect, it was found that Star Excursion Balance Test had an inter-tester reliability ranging from 0.35-0.93.[66] It also had a high test-retest reliability from 0.84-0.92.[67] This test has also been shown to be effective as a screening tool for various musculoskeletal conditions. A significant difference in scores was found between healthy participants and those with chronic ankle instability.[68] It was also able to differentiate between participants who had received an ACL reconstruction and those with no injury history.[67]

The Balance Error Scoring System, or BESS, was developed primarily as a tool for sports medicine clinicians to more objectively quantify static balance.[65] It has gained popularity as a tool in concussion evaluation. While just 5% of athletic trainers reported using the BESS as a part of their concussion evaluation in 2000, this number increased to 16% in 2005, and to 26% in 2013.[69,70] The BESS protocol consists of three test positions: Double leg stance with feet together, tandem stance with the non-dominant foot in in the back, and single limb stance on the non-dominant leg. For each test position the participant is instructed to hold their hands on their hips and keep their eyes closed. Each of these positions is completed on a stable and an unstable surface. Each of these six conditions is then tested for 20 seconds.[71] The BESS is scored by counting the number of balance errors committed in each test position. These errors are: moving the hands off the hips, opening the eyes, step, stumble, or fall, abduction or flexion of the hip beyond 30°, lifting of the forefoot or heel off the testing surface, or remaining out of the proper testing surface for greater than 5 seconds.[17] Each test condition has a maximum score of 10, which allows for a maximum overall score of 60. Compared to other clinical balance tests the BESS has a moderate to high intra-rater reliability (0.60-0.98)[19,40,53,72] and inter-rater reliability (0.57-0.96).[21,65] One of the possible reasons for the large range in observed reliability is the experience of the examiners, which ranged from 10 to 150+ hours of previous testing.

BESS scores can also be affected by factors which alter balance ability as discussed earlier including fatigue[7,8] and a distracting testing environment such as a sports sideline.[73] It has also been found that each of the six different test conditions shows vastly different results. In one study intra-rater reliability varied from 0.50 on the foam single leg condition to 0.88 on the firm single leg.[21] The same study found that the minimum detectable change (MDC), or the amount that a score would have to change to conclude that it was due to a balance deficit and not tester error, was a 7.3-point difference. This MDC accounted for nearly 50 percent of observed scores; meaning up to half the variation in scores between participants could be due to tester error. Currently available research supports the BESS as a clinical test of balance with moderate to high inter-rater and intra-rater reliability. [18,21]It can also detect balance deficits seen after a concussion or musculoskeletal injury when compared to an accurate baseline.[11,18] However the subjective nature of error scoring and the training needed to accurately note these errors may account for the large MDC. Overall the BESS has been demonstrated to be effective clinical balance test for sports medicine professionals for use in a clinic setting and in a sports setting for acute evaluation. As with the majority of clinical balance tests however, it only counts errors and does not take into account the quality of balance.

Sensory Organization Test

The NeuroCom Smart Balance Master (NeuroCom International Inc., Clackamas, OR) is a force plate setup surrounded on three sides with a moveable screen. One test that can be completed with this setup is the Sensory Organization Test. This test provides a measure of overall balance which can discriminate between the visual, vestibular, and somatosensory systems in the case that the participant is unable to integrate one or more of these systems into their balance strategy.[13] The test consists of six different trials in which one or more of the sensory systems are systematically inhibited. Visual input is removed by having the participant close their eyes. Both the visual surrounding and the force plate surface can tilt in an anterior posterior direction at the same rate as the participant's postural sway. This is termed "sway referencing". This provides either inaccurate vestibular input (surrounding sway referenced) or inaccurate proprioceptive input (support surface sway referenced). Three 20-second trials are completed for each condition.

Once all trials are completed the participant receives an equilibrium score for each condition, which is an average of each trial, and a composite equilibrium score. This is a weighted average of the scores from each separate condition. The SOT has been used in numerous studies as an overall balance measure,[13,29,49,62,74-77] with a fair to good test-retest reliability.[75,77] Wrisley and colleagues found that learning effects are present for several of the testing conditions, which plateau after the third testing session. This same study also determined that a composite score change greater than 8 points was most likely due to a change in balance ability and not testing variability.[75] The SOT has been shown effective in multiple studies at detecting changes in balance due to mild head injury.[13,29,49] It is also able to detect changes in balance due to age.[76]

The SOT provides a solution to many commonly used clinical tests. Unlike force plate setups it provides the clinician with an overall equilibrium score that does not require extensive data reduction. It is also relatively easy to set up and does not require the application of sensors or markers to the body. However, the SOT does have several drawbacks. It is not portable and requires the participant to visit an equipped facility for testing. The NeuroCom Smart Balance Master is most often used in vestibular or stroke rehabilitation facilities as well as research centers. Because of this, it is not a tool that is available to many patients. The device is also relatively expensive with prices ranging from $80,000 to $180,000 depending on the features purchased.

Sway Balance Test

The Sway Balance Test (SBT) is a mobile testing platform marketed for the purposes of measuring balance. The test uses the tri-axial accelerometer in smartphones to quantify the movement of the participant's body. The application uses a modified BESS protocol consisting of double leg stance, single leg stance on each limb, and tandem stance on both sides for one trial each. All stances are completed on a firm surface and held for ten seconds. During each of these stances the participant is instructed to hold the device firmly against their chest with both hands.

Once all five test conditions are completed the participant receives a 0-100 score for each condition and a 0-100 composite score. To date there are only two published research studies available which use the Sway Balance Test.[24,25] One of these compared scores on the BESS to SBT composite scores. It found an inverse correlation between the two tests of -0.77 (as BESS scores increased, Sway Balance scores decreased).[25] A second study used a preliminary version of the SBT and solely investigated the amount of sway recorded during single leg stance with a force plate and the SBT. This study used the "Anterior Posterior Sway Index" produced by the Biodex Balance System (Biodex, Inc., Shirley, NY). Arnold and Schmitz outlined the equation used to calculate this index.[78] The Investigators then used this formula to process the data obtained from the SBT. This study found no significant difference between the scores recorded by the two devices.[24] There is no research currently available which investigates the relationship between laboratory measures of center of pressure or center of mass and the form of the SBT that is commercially available. The study that did use a force plate measure also only investigated anterior and posterior sway and did not measure medial and lateral sway.

Summary of Rationale for the Study

Currently available research supports the need for objective balance testing for multiple healthcare fields. To date there are very few widely available clinical tests that exhibit strong reliability while providing clinician-friendly objective data. The use of accelerometers is widely supported in the literature for multiple placements including the sternum.[27,63] [23,61]There is also promising research on the use of smartphone accelerometers to measure balance. The Sway Balance Test has the potential to be a valuable tool to clinicians that may provide an objective balance measure, although more research is needed as the Sway Balance Test measures trunk movement and does not account for a user "tapping down" their feet to stabilize themselves. There is only limited research currently available which attempts to correlate scores on the Sway Balance Test to commonly used objective measures such as force plate data or stand-alone accelerometer data. One of the two currently published studies on the SBT also used a developmental version of the software, which did not use the balance algorithm currently utilized in SBT. Prior to being accepted as a clinically useful tool, more research is needed on the validity and reliability of the SBT relative to force plate data, commonly accepted as a gold standard for measuring balance.

We investigated if a significant correlation exists between the SBT and the sensory organization test. We also investigated the relationship between center of pressure plate measurements and results from the commercially available SBT algorithm, as well as the relationship between measurements obtained for a sternal position marker and the SBT, which have not yet been investigated. Finally, we assessed the reliability of the SBT in comparison to traditional force plate measures of balance. These relationships have not been investigated in the literature, and results could influence the acceptance of the SBT in clinical practice.

CHAPTER III

METHODS

Participants

We recruited a convenience sample of healthy, collegiate-aged males and females ages 18-28 (N=24, 12 male and 12 female; age=21.2 ± 1.4 yrs., height=175.1 cm ± 9.7, weight=74.3 kg ± 18.3). Participants were excluded from this study if they had a history of lower extremity surgery, were currently modifying activity due to a concussion, or were currently experiencing any symptoms associated with a lower extremity injury that prevented them from walking normally. All participants completed a basic demographic form, which included history of concussion or musculoskeletal injury. Prior to participation all participants read and signed an informed consent form approved by our institutional review board.

Instrumentation

Sway Balance Test[79] *(SBT)*(Sway Medical, LLC, Tulsa OK): The SBT consists solely of a smartphone held firmly against the participant's chest with both hands for five testing conditions, each lasting 10 seconds: feet together, tandem stance with the left foot in back, tandem stance with the right foot in back, single leg stance on the left leg, and single leg stance on the right leg (Figure 3.1).[79] After testing, a proprietary internal algorithm computes a 0-100 score for each condition, where a higher score indicates better balance performance. An average of the five conditions is then calculated resulting in a 0-100 overall score, which served as the outcome for this tool. This measure is also the primary outcome recommended for use by the company manufacturing the SBT.

Kinetic and Kinematic Measures: Center of pressure data were recorded using a single Bertec 4060-NC piezoelectric force plate (Bertec Corp, Columbus, OH). Data were collected at 100 Hz using Motion Monitor software (version 6.74; Innovative Sports Training, Inc., Chicago, IL). A single Motion Star electromagnetic motion tracker (Ascension Technologies, Inc., Burlington, VT) was attached to the manubrium of the sternum (Figure 3.2). This collected position data in the frontal, sagittal, and transverse planes at 100 Hz using Motion Monitor software. Kinetic and kinematic data were reduced to yield the primary outcomes of interest, which included sway speed, total excursion, and 95% elliptical sway area.

NeuroCom Sensory Organization Test (SOT) (NeuroCom International, Clackamas, Oregon)*:* The SOT is a clinical test that is conducted using the EquiTest Balance Master System. This test protocol is commonly used for balance assessment and vestibular rehabilitation in various clinical settings and has been previously described in detail.[74,76,77] It consists of dual force plates (data collected at 100 Hz) with a three-sided surround. Both the support surface and the surround can tilt in relation to the participant, which is termed "sway referencing". The SOT protocol consists of three 20 second trials of six different conditions: eyes open on a firm surface, eyes closed on a firm surface, eyes open with a sway referenced visual surround, eyes open with a sway referenced support surface, eyes closed with a sway referenced support surface, and eyes open with a sway referenced surround and support surface (Figure 3.3). From these six conditions a Composite Equilibrium Score is computed, with a higher score indicating better balance performance. The total composite equilibrium score served as the outcome of interest from the SOT.

Procedures

Participants completed two testing sessions 7 to 14 days apart (mean 8±1.6 days). During each testing session participants completed the Sensory Organization Test as well as the SBT protocol. Force plate and sternal marker measurements were taken concurrently during the SBT protocol. SBT protocol and Sensory Organization Testing were completed in a counterbalanced order.

Prior to completing the SBT, the electromagnetic sensor was affixed to the manubrium of the sternum with double-sided tape and participants were positioned on the force plate. Participants were instructed on proper positioning of the phone mid-sternum to ensure there was no contact between the phone and the sensor. They then completed one orientation trial of a complete SBT test, which was not recorded.

During the SBT protocol the participants were shown instructions on the device screen for positioning, and the investigator instructed them to position themselves using the same instructions provided on the screen. Once in position the "begin test" button was pressed, giving the participant three seconds to hold the device to their chest and steady themselves. The primary investigator used a trigger device to denote the beginning of each ten-second trial when analyzing the data. The trigger was pressed when an audible tone was made by the phone to indicate the beginning of a trial. After each trial the participant was instructed to relax for approximately ten seconds before beginning the next test condition. After all five conditions were completed, the participant was able to rest for one minute, and then completed this process again for a total of three complete tests. To obtain accurate force plate data, it was necessary for the participant to not tap the ground off of the force plate during a trial. If this occurred, the current SBT protocol was restarted from the first condition. If a participant had been unable to complete three full SBT protocols out of five attempts they would have been excluded from the study. However, all participants were able to complete their testing within this limit. These same procedures were completed during the second testing session for each participant.

Data Reduction

Sway Balance Test overall scores for the three completed tests were ensemble averaged to produce one outcome measure for each session. The same process was completed for center of pressure and sternal position marker data for elliptical sway area, sway speed, and total excursion. Analog force plate data were converted to digital data using an analog-to-digital converter board to allow for computer analysis. The force plate and motion sensor data were then filtered using a 10-Hz fourth order low pass Butterworth filter. The X and Y force plate coordinates were used to compute the center of pressure. Custom Matlab software (The Mathworks, Inc., Natick, MA) was used to isolate data during the SBT protocol for all center of pressure and sternal position marker data. Center of pressure movement was used to calculate average sway speed, 95% elliptical sway area, and total excursion. To determine the elliptical sway area, an ellipse was fit to the data that contained 95% of the center of pressure data points for each trial. The major and minor axes were then used to calculate the area. Total excursion was calculated by determining the total length of the path of movement of the center of pressure over the course of each trial. This value was then divided by the ten-second trial length to determine sway speed. For sternal position data, X, Y, and Z coordinate data were recorded using the electromagnetic sensor placed on the sternum. For this study only X and Y coordinates were used to calculate sway speed, elliptical sway area and total excursion as outlined above. Three full trials of each Sensory Organization Test condition were completed during each testing session. The first trial of each testing session was used as an orientation trial to the task and discarded. Composite equilibrium score was calculated from the remaining two trials using the algorithm provided by the manufacturer of the device.

Statistical Analysis

A power analysis was completed which determined that to detect a significant correlation of 0.250 using a two sided test, an $\alpha=0.05$, and power=80%, the required sample size was 22. IBM SPSS Statistics software version 22 (IBM, Endicott, New York) was used for all analysis. Correlation between averaged SBT scores and each outcome variable (SS, ESA, Excursion) were completed for both center of pressure data and sternal position marker data and the Sensory Organization Test data. This was done using a bivariate Pearson correlation for each separate variable (Table 3.1). Intraclass correlation coefficients (2,k) and Standard Errors of Measurement (SEM) were used to determine test-retest reliability (Table 3.1) across the two testing sessions for the SBT, Sensory Organization Test, center of pressure, and sternal position marker data. A 2,k model was used as only one rater was used (in this study the SBT, force plate, sternal position marker, and Sensory Organization Test acted as raters). However, we would like our results to be generalizable to slightly different testing environments if the same procedures were used.

Table 3.1: Statistical analysis procedures

Question	Description	Data Source	Comparison	Method
1a	Are Sway Balance Test scores correlated with force plate balance measures?	Performance on Sway Balance Test (SBT) and force plate measurements of COP during the SBT	1) 95% COP Elliptical Sway Area vs. SBT Total Score 2) Total COP Excursion vs. SBT Score 3) COP Sway Speed vs. SBT Total Score	Three bivariate Pearson correlations with 95% Cis (we additionally ran three correlations for each SBT condition)
1b	Are Sway Balance Test scores correlated with sternal position marker measurements?	Performance on the SBT and sternal position marker (SPM) measurements during the SBT	1) 95% SMP Elliptical Sway Area vs. Total Score 2) Total SPM Excursion vs. Total Score 3) SPM Sway Speed vs. Total Score	Three bivariate Pearson correlations with 95% CIs (we additionally ran three correlations for each SBT condition)
1c	Are Sway Balance Test scores correlated with SOT composite scores?	Performance on the SBT and performance on the SOT	1) SOT Composite Equilibrium Score vs. Total Score	One bivariate Pearson correlation with 95% CIs
2	Will the reliability of traditional force plate and sternal marker position be higher than that of the Sway Balance Test?	Performance on SBT	1) SBT Averaged Total Score Time 1 vs. SBT Averaged Total Score Time 2 2&3) 95% COP and SPM Elliptical Sway Area 4&5) Total COP and SP Excursion 6&7) COP and SPM Sway Speed	Seven Intraclass correlations coefficients ($ICC_{2,k),}$ and Standard Error of Measurements (SEM)

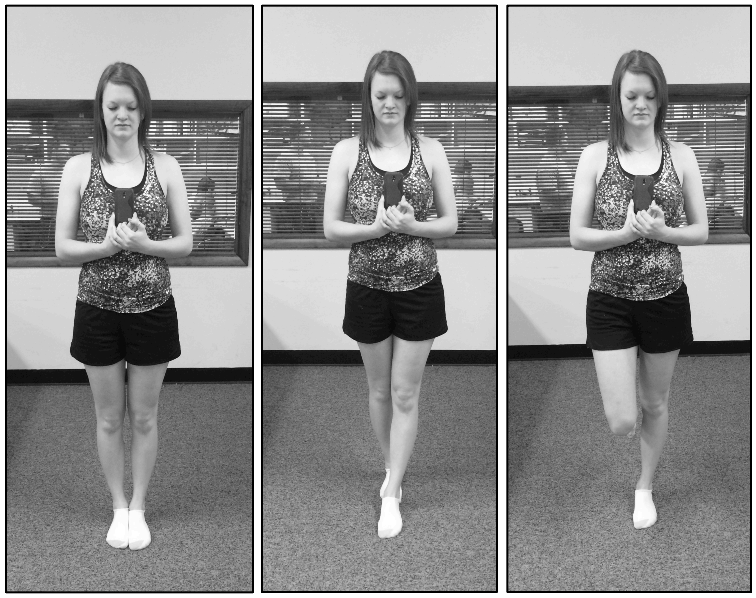

Figure 3.1. Sway Balance Test stance conditions left to right: double leg stance, tandem stance completed with once with each leg in back, single leg stance completed once with each leg.

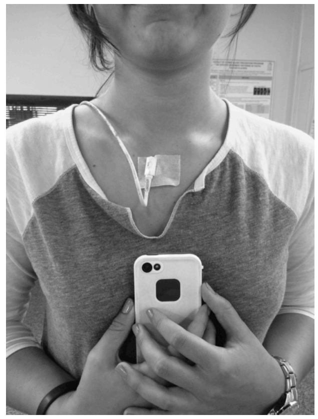

Figure 3.2. Phone and sensor positioning.

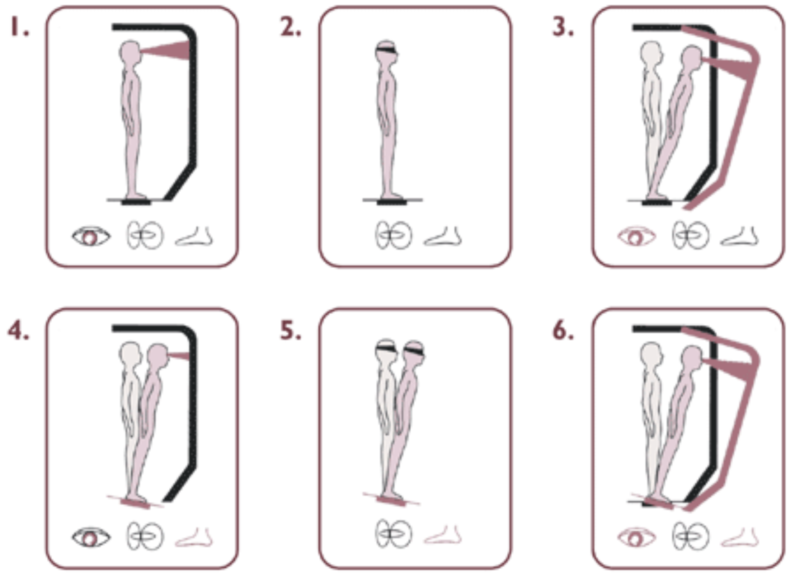

Figure 3.3. SOT conditions: eyes open on a firm surface, eyes closed on a firm surface, eyes open with a sway referenced visual surround, eyes open with a sway referenced support surface, eyes closed with a sway referenced support surface, and eyes open with a sway referenced surround and support surface.

CHAPTER IV

MANUSCRIPT

INTRODUCTION

Balance is affected acutely post-concussion, and deficits may last for several days.[11-13] Because balance performance is an effective diagnostic marker of concussion, clinical practice guidelines recommend using balance testing during concussion evaluation and follow-up testing.[14,15] Objective balance measures are often obtained from force plates on which the participant attempts to maintain their balance, or from accelerometers applied to various points on the body.[3,16] However, these methods are often costly and produce a large amount of raw data which is not immediately useful to the clinician.[17] Thus, these measures are not feasible for use in most clinical settings. While commonly used clinical tests are easy to perform and affordable, there are several drawbacks. These include decreased sensitivity, subjective “balance quality” measures, and scores that may be difficult to compare over time.[14,18]

An example of one such clinical task is the Balance Error Scoring System (BESS). The BESS consists of three different positions held for 20 seconds each on both a stable and unstable surface. The BESS scoring system relies on “errors” which include the participant losing their balance or touching a foot on the ground. Several studies have found large variance in the amount of errors detected during the test.[19-21] While the BESS is a good clinical tool, more sensitive and objective balance assessment tests may improve patient care.

A test that bridges the gap between laboratory force plate tests and clinical balance tests is the Sensory Organization Test. This uses a force plate and a moveable surround. A subject completes six 20 second trials in which the eyes are opened or closed, the force plate surface tilts in response to the subject's movement, or the surround tilts in a similar manner. An algorithm is then used to produce a 0-100 "composite equilibrium score". This test is easy to administer with minimal training and does not require extensive data reduction. However it is expensive and non-portable, so it is not used in many clinical settings.

Accelerometers encompassed in many smartphones have the potential to be feasible balance assessment tools and allow for objective data collection. Smartphone applications that utilize the features of the accelerometer are widely available and relatively cheap, resulting in extremely portable and accessible accelerometer devices.[22] The output measured from these smartphone accelerometers has been found to be valid and reliable in measuring standing balance compared to laboratory measures.[23,24]

The Sway Balance Test (SBT, SWAY Medical, Tulsa, OK, USA), which is currently available for purchase, is a mobile balance test that has been cleared by the United States Food and Drug Administration. This test uses the accelerometers in a compatible smartphone to quantify balance using a modified BESS protocol. The phone is held against the chest and each condition is completed on a firm surface. Tandem and single leg stances are completed on both sides. Unlike the BESS, each trial is 10 seconds. From these data the SBT application gives the clinician a 0-100 balance score, with a higher score indicating better balance. A recent study utilizing a developmental version of the SBT (not the current version) observed a moderate correlation between the anterior and posterior sway measured by the phone and scores on the Biodex Balance System SD (Biodex Medical Systems, Shirley, NY, USA).[24] A second study observed that individuals with worse BESS scores (higher) also had worse (lower) SBT scores.[25] At this time there is little research available that investigates the concurrent relationship between the current commercially available version of the SBT and commonly accepted laboratory and clinical balance measures.

Therefore, the primary purpose of this study was to examine if scores obtained from the Sway Balance Test correlate with traditional center of pressure and clinical measures of balance in healthy college students. We also investigated how the reliability of the SBT compares to traditional laboratory measures of balance. We hypothesized the SBT overall score would be moderately ($r=-0.5$ to -0.7) inversely correlated with center of pressure measures, strongly ($r>0.7$) inversely correlated with sternal position marker measures, and moderately positively correlated with the Sensory Organization Test. We also hypothesized the SBT would have a lower reliability than the center of pressure and sternal position marker balance measures.

METHODS

Research Design

We conducted a cross sectional study of healthy college aged individuals to assess correlation between the Sway Balance Test (SBT) and more traditional measures of balance. Testing was repeated at a separate time point to determine reliability of study measures. Data were collected over a six-month period, with participants completing two testing sessions 7-14 (mean 8.1±1.6) days apart. Participants completed the SBT while center of pressure and sternal position marker data were recorded. They also completed SOT testing. The SBT and SOT were completed in a counterbalanced order. The Institutional Review Board at the University of North

Carolina at Chapel Hill approved all testing procedures and demographic questionnaires prior to study initiation.

Participants

A convenience sample of 12 male and 12 female healthy, college ages subjects between the ages of 18 and 28 years agreed to take part in the study. The average age of our participants was 21±1.4 years. The mean weight was 74±18.3 kg, while the mean height was 175±9.7 cm. Participants were excluded from this study if they were outside the 18-28 age range, had a history of any lower extremity surgery, were modifying their activity due to a concussion, or had any injury at the time of the study which affected their ability to walk normally.

Instrumentation

Sway Balance Test[79] (SBT; Sway Medical, LLC, Tulsa OK): The SBT consists of five testing conditions, each lasting 10 seconds: feet together, tandem stance with the left foot in back, tandem stance with the right foot in back, single leg stance on the left leg, and single leg stance on the right leg (Figure 4.1).[79] After testing, a proprietary internal algorithm computed a 0-100 score for each condition with a higher score indicating better performance. An average of the five conditions was calculated to result in a 0-100 overall sway score.

Kinetic and Kinematic Measures: Center of pressure data were recorded using a single Bertec 4060-NC piezoelectric force plate (Bertec Corp, Columbus, OH). Data were collected at 100 Hz using Motion Monitor software (version 6.74; Innovative Sports Training, Inc., Chicago, IL). A single Motion Star electromagnetic motion-tracking sensor (Ascension Technologies, Inc., Burlington, VT) was attached over the manubrium of the sternum (Figure 4.2). This collected position data in the frontal, sagittal, and transverse planes at 100 Hz using Motion Monitor software.

NeuroCom Sensory Organization Test (SOT) (NeuroCom International, Clackamas, Oregon)*:* The SOT is a clinical test that is conducted using the EquiTest Balance Master System. This test has been previously described in detail.[74,76,77] It consists of dual force plates with a three-sided surround. Both the support surface and the surround tilt in relation to the participant's center of pressure, which is termed "sway referencing". The protocol consists of three 20-second trials of six different conditions, which are described in Figure 4.3. From these six conditions a 0-100 Composite Equilibrium Score is computed, with a higher score indicating better balance performance. The total composite equilibrium score served as the outcome of interest from the SOT.

Procedures

Prior to completing the SBT participants removed both shoes and socks to avoid any discrepancy due to shoe type. The electromagnetic sensor was then affixed to the manubrium of the sternum with double-sided tape and participants were positioned on the force plate. Participants were instructed on proper positioning of the phone mid-sternum to ensure there was no contact between the phone and sensor. They then completed one full Sway Balance Test as an orientation, which was not recorded.

During the SBT study protocol the participants completed the test as using Sway Medical's recommendations. They were shown instructions on the device screen for positioning, and the investigator instructed them using the same instructions provided on the screen. Once in position the participants pressed the "begin test" button on the phone, giving them three seconds to hold the device to their chest and steady themselves. The primary investigator used a trigger device synced with the Motion Monitor software to denote the beginning of each ten-second trial. After each trial the participant was instructed to relax for approximately ten seconds before beginning the next test condition. After all five conditions were completed the participant rested for one minute before completing this process for a total of three full tests. If the subject stepped off the force plate, opened their eyes, or moved the phone off their chest during a test, the SBT protocol was restarted from the first condition (beginning of the test). If a participant were to be unable to complete three full SBT protocols out of five attempts they would have been excluded from the study. However, all participants were able to complete three full tests within five attempts. Out of 48 total tests, 2 participants took 4 attempts and 2 took 5. These same procedures were completed during the second testing session for each participant.

Prior to completing the Sensory Organization Test participants again removed both their shoes and socks. They were then positioned on the device and instructed according to the manufacturers guidelines. They completed three trials of each condition. The first two trials were completed in order, while the conditions in the third trial were completed in a random order. If a participant fell or used the safety straps for support the condition was marked as a fall and discontinued.

Data Reduction

We contacted Sway Medical in an attempt to determine the specific outcome measurements used to compute the overall Sway score. However, they declined to provide us with more information on the outcome measures used in their algorithm. Thus, we analyzed the overall Sway score, as this is the most clinically useful, as well as the Sway condition scores. Sway Balance Test overall scores for the three completed tests were ensemble averaged to produce one outcome measure for each session. The same process was completed for center of pressure and sternal position marker data for each variable of interest.

Analog force plate data were converted to digital data using an analog-to-digital converter board to allow for computer analysis. Center of pressure and motion sensor data were then filtered using a 10-Hz fourth order low pass Butterworth filter. Custom Matlab software (The Mathworks, Inc., Natick, MA) was used to isolate all center of pressure and sternal position marker data during each 10-second trial. Sagittal and frontal plane center of pressure data were plotted over the full 10-second trial length, which was measured to determine total excursion (cm). Excursion was divided by the 10-second trial length to determine sway speed (cm/s). To determine the elliptical sway area, an ellipse was created that contained 95% of the center of pressure data points for each trial. The major and minor axes were then used to calculate the area. Sagittal and frontal plane coordinates were used from the sternal position marker to calculate sway speed, elliptical sway area, and total excursion as outlined above.

Three full tests were completed using the SOT during each testing session. The first trial of each condition was used as an orientation trial to the task and discarded. Composite equilibrium score was calculated from the remaining two trials using the algorithm provided by the manufacturer of the device.

Statistical Analysis

A power analysis determined that to detect a significant correlation of 0.250 using a two sided test, an α=0.05, and power=80%, the required sample size was 22. IBM SPSS Statistics software version 22 (IBM, Endicott, New York) was used for all analysis. Pearson Correlation between averaged SBT scores and each outcome variable (sway speed, 95% elliptical sway area, total excursion) were completed for center of pressure data, sternal position marker data, and the SOT composite equilibrium score. Intraclass correlation coefficients ($ICC_{2,k}$) and Standard

Errors of Measurement (SEM) were used to determine test-retest reliability across the two testing sessions for the SBT, center of pressure, and sternal position marker data.

RESULTS

SBT Correlations with Center of Pressure Measures and the Sensory Organization Test

SBT overall score was stongly inversely correlated with center of pressure elliptical sway area (r=-0.816, p<0.001, CI [-1.000, -.0560]) (Figure 4.1) and center of pressure sway speed (r= -0.888, p<0.001, CI [-1.000, -0.684]) (Figure 4.2). When exploring individual SBT stance conditions, a small inverse correlation was found between SBT double leg outcome score and center of pressure elliptical sway area (r=-0.247; p<0.001). All other SBT stance condition outcome scores were inversely correlated to both center of pressure speed and center of pressure area (r>0., p<0.001) (Table 4.2). SBT overall score was also correlated with SOT composite score (r=0.420, p=0.041).

SBT Correlations with Sternal Position Marker Measures

SBT overall score was inversely correlated to sternal position marker elliptical sway area (r=-0.899, p<0.001, CI [-1.000, -0.703]) (Figure 4.3). No significant correlation was found between SBT overall score and sternal position marker sway speed (r=-0.314, p=0.135, CI [-0.734, 0.106]) (Figure 4.4). No significant correlations were observed between SBT double leg outcome score and sternal position marker sway speed, tandem right outcome score and sternal position marker sway speed, tandem left outcome score and sternal position marker sway speed, or between SBT double leg outcome score and sternal position marker elliptical sway area. All other SBT stance condition outcome scores were inversely correlated with sternal position marker area (p<0.001) and sternal position marker speed (p<0.15) (Table 4.2).

Force Plate Measures Correlations with Sternal Position Marker Measures

Force plate elliptical sway area was strongly positively correlated with sternal position marker elliptical sway area ($r=0.896$, $p<0.001$). Force plate speed and sternal position marker speed were weakly correlated ($r=0.439$, $p=0.032$).

SBT, Center of Pressure, and Sternal Position Marker Reliability

The Sway Balance Test overall score was found to have a high test-retest reliability ($ICC_{2,k}$) of 0.942. Center of pressure sway speed measurements were highly reliable (0.952), while center of pressure elliptical sway area (0.695) and sternal position marker elliptical sway area (0.727) had moderate test-retest reliability. Sternal position marker speed had a relatively low reliability of 0.425 (Table 4.3).

Reliability measures varied widely when comparing between stance conditions within the Sway Balance Test. “Right sided” stances (i.e. tandem right foot forward and single leg right) had the highest reliability at 0.941 and 0.940 respectively. This was followed by single leg left (0.791), double leg (0.720), and tandem left (0.477). The Sensory Organization Test reliability was also high (ICC=0.880; SEM=2.12).

DISCUSSION

Our most important study finding was that SBT overall scores were strongly correlated to commonly used laboratory measures of sway speed and elliptical sway area obtained from center of pressure data. SBT scores were also strongly correlated with elliptical sway area measures obtained from a sternal position marker. These findings suggest that the SBT overall score is a concurrently valid balance measurement. This strong association suggests that the phenomenon measured during the SBT is highly related to force plate sway speed and elliptical sway area as well as sternal position marker elliptical sway area. In our study, the SBT overall score (recommended metric) had test-retest reliability that was similar to center of pressure sway speed and higher than that of all other outcome measures including the center of pressure elliptical sway area and the Sensory Organization Test, both of which have been validated in numerous studies.[16,77,80]

SBT Overall Score Correlation with Force Plate Measures

Previous studies using an accelerometer placed over the sternum, as with the Sway balance test, have considered it a vertical projection of the center of mass.[16,61] It is well documented that center of pressure as measured with a force plate and the center of mass will be moving in opposite directions of each other at many time points when measuring balance.[2,16,59] For example if the center of mass of a subject moves anteriorly the subject will plantarflex at the ankle thus moving the center of pressure anteriorly as well. This plantarflexion will cause the center of mass to move posterior while the center of pressure continues moving anterior until the center of mass and center of pressure equalize.[2] In this context, the center of pressure can be seen as the body's attempt to control movement of the center of mass. While these two measurements calculate outcomes in different ways, they are measuring the same phenomenon. If the center of mass moves at a greater speed or a greater distance, the center of pressure will have to move in a similar nature to respond and maintain upright posture. During the SBT, the phone is not held over the estimated center of mass, but over the sternum. Previous studies have shown that a sensor placed on the sternum will move in a similar direction and magnitude to the center of mass.[16,61]

Our findings showed very strong agreement between SBT overall scores and center of pressure measurements of sway speed and elliptical sway area. This suggests that sternal placement of a phone during the SBT is valid for measuring balance in a variety of stances. As center of pressure speed and elliptical sway area are commonly seen as “gold standard” balance measurements, our finding of strong correlations between these two measures and the SBT (elliptical sway area r=-0.816, sway speed r=-0.888) suggest the SBT could be a valid alternative to force plate measurements in situations where force plates are too costly or impractical such as sports medicine settings, sideline testing, or during large screening sessions.

SBT Overall Score Correlation with Sternal Position Marker Measures

As discussed earlier, during the SBT the phone is held over the sternum, much higher than the estimated center of mass. This is the first study to use sternum position marker movement to measure elliptical sway area and sway speed. Previous studies have used acceleration root mean square or step length and velocity.[63 61] As such it is important to note that sternal position marker sway speed and elliptical sway area are not validated balance measures. However, the strong correlation between SBT overall scores and sternal position marker elliptical sway area suggests that sternal position marker elliptical sway area, center of pressure elliptical sway area and sway speed, and the SBT are all measuring similar phenomenon which was not measured in a similar manner by sternal position marker sway speed.

It is possible that the SBT algorithm uses the height of the participant to estimate the movement of their center of mass, so any sway speed that is used to calculate the SBT outcome score would be different that the sway speed seen at the sternum. As has been discussed previously, many studies have seen a strong correlation between center of mass and center of pressure movement, which would account for the strong agreement between SBT overall score and center of pressure sway speed.[27,59,81]

A second possible reason for the lack of correlation between sternal position marker sway speed and SBT overall scores may be a lack of linear relationship between speed of movement seen at the feet and at the trunk. As elliptical square area does not have a unit of time, it is possible that difference in speed would not cause a change in elliptical area if there were a similar total range of movement.

Sternal position marker measurements were initially added to this study to better understand the motions being seen at the phone held to the sternum, and therefore the algorithm used for the SBT. Because of this, a lack of correlation between sternal position marker sway speed and SBT outcome scores should not impact how the test is used clinically. We observed a strong correlation between the laboratory standard of center of pressure sway speed and elliptical sway area. This shows that while little in know about the algorithm and mechanisms used to create the SBT outcome score, it is a valid tool for measuring balance, utilizing current validation standards.

SBT Overall Score Correlation with the Sensory Organization Test

SBT overall scores had a weak positive correlation (r=0.420) with composite equilibrium scores on the Sensory Organization Test, which was not in line with our original hypothesis. One possible reason for the weak correlation is the way in which scores are calculated for each test. The Sensory Organization Test only uses the total range of anterior and posterior center of pressure movement to determine how much of a subject's available anterior and posterior sway has been used (using 100 percent of possible sway in either direction results in a fall, leading to a score of zero for that condition). Conversely the SBT may factor in medial/lateral movement and speed as well. It is also important to note that the SBT and the Sensory Organization Test challenge the participant's balance abilities in different ways. The SBT uses different stance conditions, which alter the participant's base of support, therefore measuring their ability to stabilize themselves on a single limb. Conversely in the SOT the participant remains in a double leg stance for the entire test, while the conditions around them are altered. This takes into account their ability to integrate multiple systems, which are not challenged to the same level during the SBT.

During many athletic tasks, a participant must stabilize themself on one foot or in a position with a small base of support. For these patients, or during quick balance screenings, the SBT may be a good tool. This is due to its convenience, ease of use, and because all stances are completed on a stable surface, similar to sporting events and most daily activities. However, if a clinician wishes to diagnose a balance disorder or determine the cause of a balance deficit, the Sensory Organization Test may be the best tool due to the reasons mentioned above: the different conditions attempt to isolate and challenge the various systems used to maintain balance which can be effected by age, disease, or head injury.[29,48,76]

Correlation of SBT Condition Scores to Center of Pressure and Sternal Position Marker Outcome Measures

When comparing the SBT to center of pressure and sternal position marker outcomes by stance condition, a similar trend emerges. Sternal position marker speed had either no correlation or a poor correlation with all SBT condition scores. Sternal position marker elliptical sway area, however, was strongly inversely correlated with all SBT condition scores except double leg stance. As discussed earlier, sternal position marker movement has not been previously validated as a balance measure, and it is possible that marker placement or different speeds of movement between the center of pressure and sternum could lead to these differences.

The double leg stance condition showed either a poor or no correlation with all of the FP and SPM balance measures. This is most likely due to the ceiling effect present with double leg stance. Most subjects received a SBT condition score of near or at 100 (max possible score) for this condition (mean 99.58, sd 0.63), while there was no ceiling effect for the sternal position marker measurements. Many previous studies on the Balance Error Scoring System have noted a low utility of the double leg stance.[18,21] In this condition, many subjects had no "errors", similar to a participant receiving a score of 100 on the SBT. If used clinically it should be noted that a high SBT condition score on double leg stance may not be meaningful in healthy subjects. All other conditions were strongly correlated with center of pressure sway speed, center of pressure elliptical sway area, and sternal position marker elliptical sway area.

While the double leg condition may have a low correlation to force plate and sternal position marker outcomes compared to the other stances, it is important to note how the SBT is used clinically. It is recommended that the clinician perform three full tests (as we did in this investigation) as a baseline measure. From this, a 95% confidence interval is calculated. After an injury the clinician can complete an additional test and the results will be compared to this confidence interval (range of scores). Therefore, we believe it is more important to consider the correlation of the test as a whole to commonly used measures as opposed comparing each stance individually. All subjects in this study performed very well on the double leg stance condition regardless of their overall scores. This has been demonstrated with the BESS in many studies,[18,21] while others show an increase in reliability after removing this stance.[19] It is unclear how completing a single test post injury would change the results of this study. Clinicians should consider completing three baseline measurements as recommended by Sway Medical. Future research should investigate the difference between a single test versus multiple tests on the validity of the SBT

Reliability of the SBT Compared to Center of Pressure and Sternal Position Marker Outcomes

The SBT's overall score reliability was similar to that of center of pressure sway speed and the Sensory Organization Test composite equilibrium scores, both commonly used balance measures. Thus, the SBT appears to be an effective balance test in healthy individuals if the average score of multiple trials is used. When analyzing the reliability of the various SBT stances it is again important to consider how the test is meant to be used clinically. While not all stance conditions of this test show high reliability, the average user of the test will only use the overall score (combination of all condition scores).

Interestingly the reliability of position scores on the tandem left stance were much lower than on that of the tandem right stance. Of our 24 participants, 19 reported being right foot dominant. While it has not been reported in the literature, this may lead to more variable balance performance on their non-dominant foot leading to a lower reliability. Anecdotally, the tandem stance was also the hardest stance for participants to correct any "unsteadiness". While in single leg stance they simply had to tap down a foot to steady themselves, but if their balance was lost in tandem stance they would often stumble or have to reset themselves which could lead to more inconsistent scores.

As stated previously, we used the average of three full Sway Balance Tests to obtain our reliability measures. However the recommendation to do this was published in a white paper by Sway Medical. It is not clearly stated in the application or on the Sway Medical website that three baseline measurements our needed. As such, many clinicians may not be aware of the recommendation to complete multiple tests. If clinicians wish to use the SBT to compare post-injury results to pre-injury baselines, care must be taken to complete the recommended three baseline tests. Based on our findings clinicians may consider completing multiple tests post-injury as well. However more research is needed on the impact of single versus multiple tests on the reliability of the SBT.

Limitations

This study used healthy recreationally active college aged students. As such it may not be generalizable to all populations including children, sedentary individuals, or the elderly. It is also important to note that this study did not examine the use of the SBT post-concussion or injury. As with all laboratory-based studies, results obtained on a playing field or other busy environment may not be the same as those obtained in a quiet lab. We also did not directly assess center of mass movement, which may have yielded different results.

Future Research

Future research should focus on the utility of the SBT in the presence of various pathologies, including concussion. This research should determine the sensitivity and specificity for balance deficits following concussion. More research is also needed to determine if the sternum is the best placement of the phone during testing sessions. Center of mass measurement could provide valuable insight into the mechanisms used to calculate the SBT outcome score. Research is also needed to determine the necessary number of tests that should be administered for optimal validity and reliability.

Conclusion

This study found the Sway Balance Test to be a concurrently valid test of balance that is highly correlated to traditional force plate measures of balance. Overall scores on the Sway Balance Test also show a high test-retest reliability similar to that of more expensive and cumbersome force plates. This suggests it can be used to measure overall balance ability in healthy subjects while being reliable over time. The SBT could be used in situations where center of pressure data would be difficult to obtain due to time, space, or monetary constraints. When using the SBT clinicians should take care to complete three full baseline tests, and it may be beneficial to complete multiple tests when assessing balance after any injury as well. It should also be noted that this study only used healthy college aged participants with a relatively high balance ability. More research is needed before the SBT can be considered comparable to center of pressure for the measurement of balance deficits due to concussion, advanced age, disease, or any other pathology.

Table 4.1. Mean and standard deviation for sway speed, excursion, and elliptical sway area variables

		Overall Score	Double Leg	Tandem Right	Tandem Left	SL Right	SL Left
Force Plate	Sway Speed (cm/s)	6.23 (1.95)	2.17 (0.78)	5.77 (2.13)	5.97 (2.16)	8.42 (3.26)	8.81 (2.96)
	Excursion (cm)	62.27 (19.49)	21.67 (7.75)	57.69 (21.27)	59.75 (21.64)	84.16 (32.56)	88.06 (29.61)
	ESA (cm^2)	2.28 (1.45)	0.60 (0.41)	1.92 (1.78)	1.98 (1.68)	3.39 (2.82)	3.48 (2.40)
Sternal Position Marker	Sway Speed (cm/s)	7.02 (3.86)	6.93 (4.90)	6.83 (4.17)	6.84 (3.81)	8.03 (4.64)	6.49 (2.79)
	Excursion (cm)	70.23 (38.58)	69.30 (49.03)	68.27 (41.73)	68.43 (38.14)	80.28 (46.36)	64.48 (27.85)
	ESA ($cm^{2)}$	3.41 (2.59)	0.96 (0.55)	0.96 (0.55)	3.12 (3.18)	5.35 (5.97)	5.39 (4.31)
Sway Balance Test		90.14 (8.84)	99.58 (0.63)	94.83 (8.15)	92.27 (9.63)	83.63 (17.3)	80.93 (14.79)

*Measurements were averaged across all three tests in testing session one

Table 4.2. Correlation and p-values for center of pressure sway speed, center of pressure elliptical sway area, sternal position marker sway speed, sternal position marker elliptical sway area, and SBT condition score

	Center of pressure sway speed (cm/s)			Center of pressure elliptical sway area (cm^2)		
SBT Stance	r	95% CI	P-value	r	95% CI	P-value
Double Leg	-0.444	-0.084, -0.048	0.030	-0.247	-0.676, 0.181	0.244
Tandem Right	-0.881	-1.000, -0.671	<0.001	-0.931	-1.000, -0.770	<0.001
Tandem Left	-0.830	-1.000, -0.583	<0.001	-0.749	-1.000, -0.456	<0.001
Single Leg Right	-0.890	-1.000, -0.688	<0.001	-0.842	-1.000, -0.603	<0.001
Single Leg Left	-0.885	-1.000, -0.679	<0.001	-0.753	-1.000, -0.462	<0.001
	Sternal position marker sway speed (cm/s)			Sternal position marker elliptical sway area (cm^2)		
SBT Stance	r	95% CI	P-value	r	95% CI	P-value
Double Leg	0.003	-0.439, 0.445	0.989	-0.116	-0.555, 0.323	0.589
Tandem Right	-0.029	-0.471, 0.413	0.892	-0.836	-1.000, -0.594	<0.001
Tandem Left	-0.255	-0.682, 0.173	0.230	-0.843	-1.000, -0.606	<0.001
Single Leg Right	-0.490	-0.875, -0.104	0.015	-0.834	-1.000, -0.591	<0.001
Single Leg Left	-0.549	-0.919, -0.180	0.005	-0.932	-1.000, -0.772	<0.001

Table 4.3: Reliability of SBT, center of pressure, and sternal position marker outcome measures

Sway speed and elliptical sway area		
	ICC $_{(2,K)}$	SEM
COP Speed	0.952	0.427 cm/s
COP Area	0.695	0.802 cm^2
SPM Speed	0.425	2.925 cm/s
SPM Area	0.727	1.351 cm^2
Sway Balance Test		
	ICC $_{(2,K)}$	SEM
Overall Score	0.942	2.129
Double Leg	0.720	0.333
Tandem Right	0.941	1.974
Tandem Left	0.477	6.964
Single Leg Right	0.940	4.238
Single Leg Left	0.791	6.761

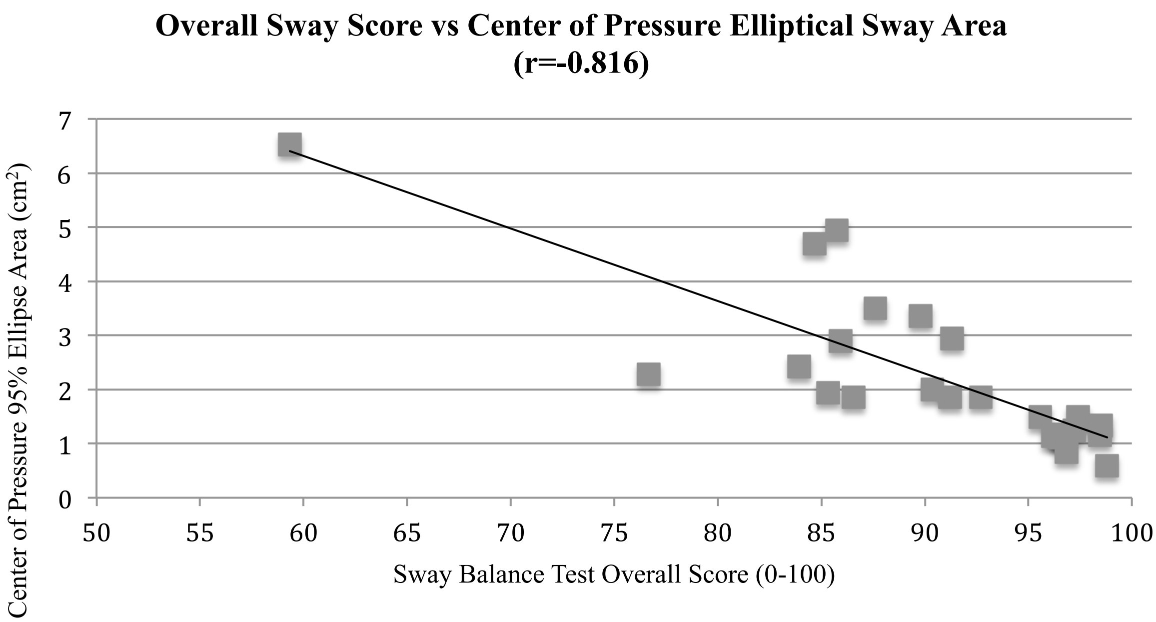

Figure 4.1. Scatterplot for correlation between Sway Balance Test overall score and center of pressure elliptical sway area

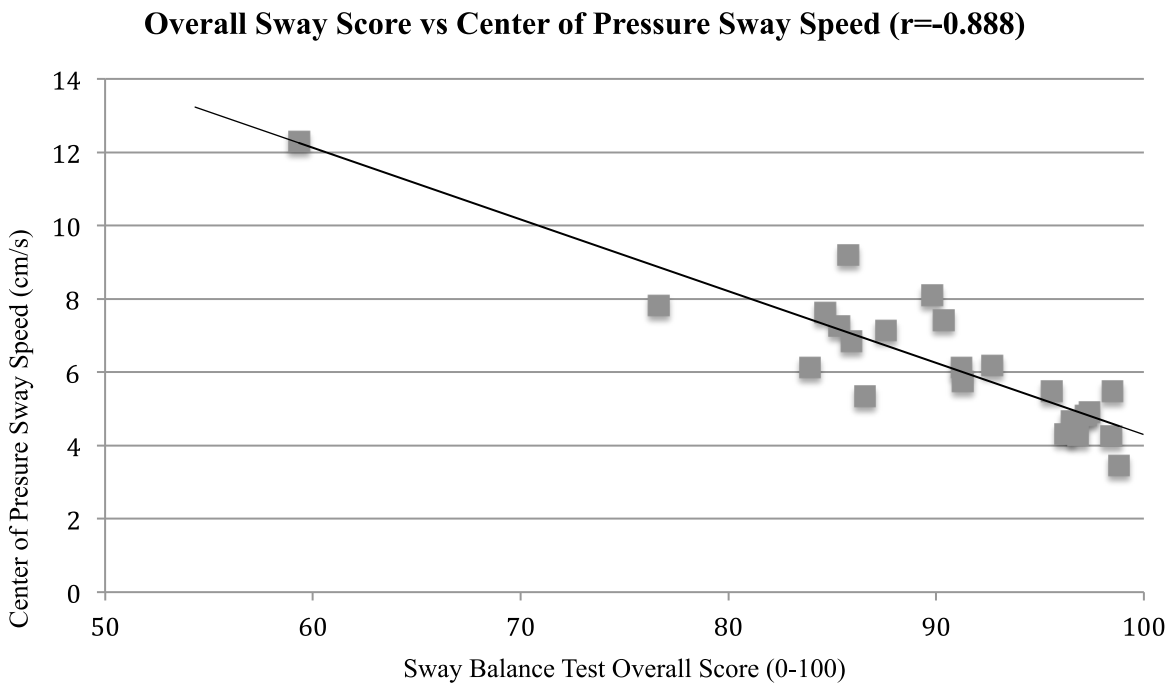

Figure 4.2. Scatterplot for correlation between Sway Balance Test overall score and center of pressure sway speed

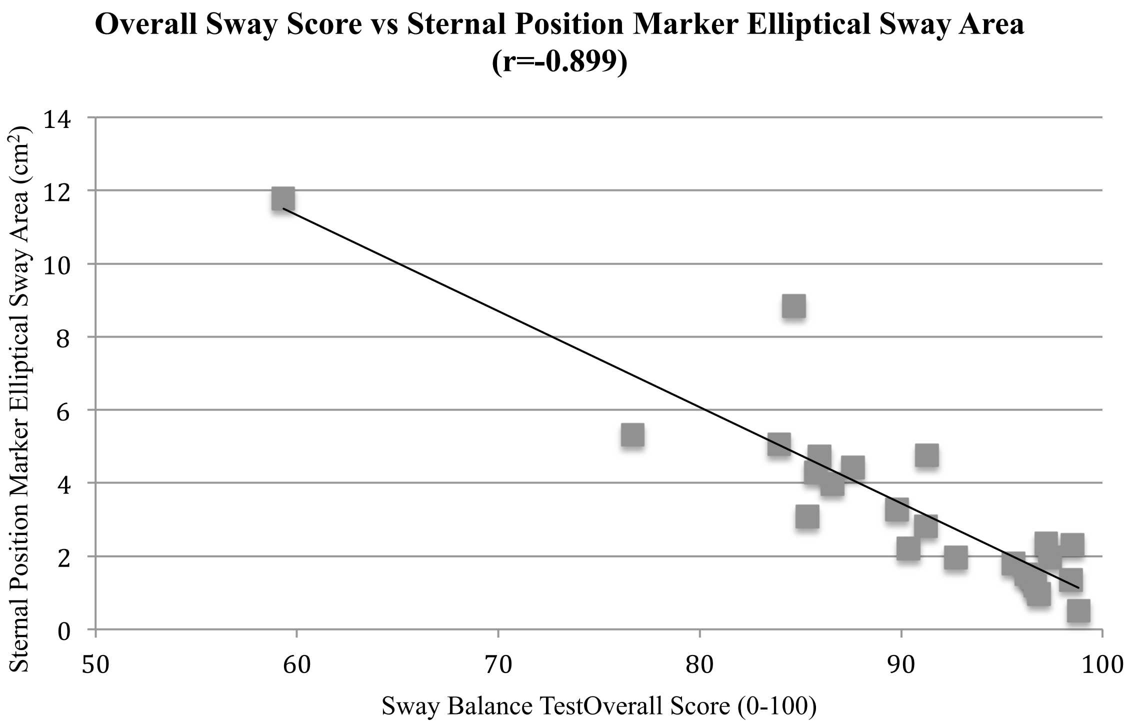

Figure 4.3. Scatterplot for correlation between Sway Balance Test overall score and sternal position marker elliptical sway area

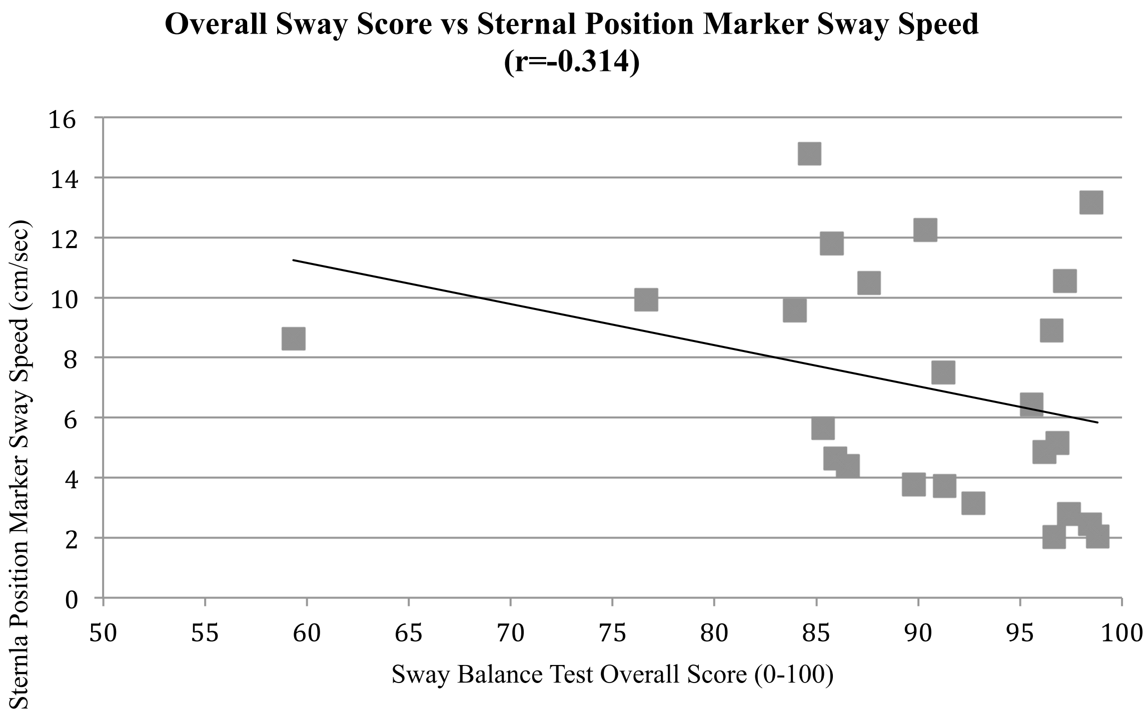

Figure 4.4. Scatterplot for correlation between Sway Balance Test overall score and sternal position marker sway speed

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