VALIDATION OF BALANCE ASSESSMENT MEASURES OF AN ACCELEROMETRIC MOBILE DEVICE APPLICATION VERSUS A BALANCE PLATFORM

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The following faculty members have examined the final copy of this thesis/dissertation for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Education with a major in Exercise Science.

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ABSTRACT

Recent technological advancements in electronics and telecommunications have provided more accessible quantitative methods of assessing balance. The latest Smartphones have built-in motion sensors called tri-axial accelerometers, which are an ideal choice for evaluating variability of movement and balance providing a non-invasive, portable method of measurement. **PURPOSE:** The purpose of this study was to compare the balance assessment measures from a mobile device application (iPod) utilizing accelerometric motion sensors against the balance assessment measures of a clinically valid and reliable balance platform (BIODEX Balance System SD). **METHODS:** 75 healthy college-aged individuals (37 male, 38 female; average age = 24.2±6.8 yr) performed a series of balance tasks over two visits (Study 1 and Study 2). During Study 1, 8 balance tests were assessed, beginning with two feet on ground (baseline) and progressively becoming more difficult and repeating them over three trials. iPod Touches with a software application to measure balance was used to assess sway. During Study 2, participants completed 4 balance assessments using a clinically validated balance platform and the iPod Touches, at the same time. **RESULTS:** Data showed that the iPod Touches were consistent with expect outcomes, based off of normative data; the more unstable the assessment the higher the balance score compared to baseline or standing with feet together eyes open without foam. Analyses of the 3 trials suggest that a familiarization test should be performed when using the iPod Touch balance application and this is consistent with other devices. Results from Study 2 showed no significant difference between the two devices when measuring without foam, but a significant difference was found between the two while balancing on foam. **CONCLUSION:** Balance scores measured by accelerometers within an iPod appear to be a valid and consistent method of measuring human balance.

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CHAPTER 1

INTRODUCTION

1.1 Overview

Balance, or postural stability, is a complex process involving coordination of multiple sensory, motor, and biomechanical components [1-4]. The purpose of balance is to maintain a specific postural alignment, such as sitting or standing, assist in voluntary movement, such as changing posture, and reacting and recovering from an external disturbance that affects stability, such as a trip, slip, or push [5]. Balance improvement has been shown to help with recovery, injury prevention, and functional performance in both young and elderly individuals, but proper assessment is required in order to implement the appropriate protocols for each person. Assessments must be reliable, valid, and reproducible in order to provide the most successful results. Many methods have been developed to assess balance, such as the Berg Balance Test, the Postural Assessment Scale for Stroke patients, the Functional Independence Measure, and the Continuous-Scale Physical Function Performance Test, which are functional tests used to measure balance, posture, and equilibrium, typically in the elderly and neurologically impaired population [6-9]. Other functional balance assessments have been developed for the use of determining postural stability after balance disturbance takes place, like the Sport Concussion Assessment Tool-version 2 (SCAT2) and The Balance Error Scoring System (BESS) [10, 11]. The BESS is considered a clinical evaluation that correlates with laboratory-based measures for criterion-related validity and construct validity [34]. With the development of all these assessments, it is clear that assessment of balance plays an important role in the health and development of functional movement for individuals.

1.2 Statement of the Problem

Though several of the aforementioned methods of balance assessment have been used in the clinical setting, many have been criticized for offering only subjective information rather than objective information. Though many balance assessment tools are being utilized, the most accessible and cost-efficient methods, though adequate, rely on subjective and qualitative measures that the test administrator observes and concludes based on his or her opinion. Objective, quantitative methods are needed to give precise measurements. There is a need for accessible and cost-efficient quantitative measures of balance that provide precise, comparative data for each subject.

Recent technological advancements in electronics and telecommunications have provided even more accessible quantitative methods of assessing balance through accelerometers in mobile devices. Despite the increase of research in the both areas of balance assessment and telecommunications, there are limited studies that apply mobile accelerometry to human balance. From those studies, the current literature indicates that accelerometry can provide accurate and reliable measures of basic temporospatial gait parameters, shock attenuation, and segmental accelerations of the body when walking, thereby providing useful insights into the motor control of normal walking, age-related differences in dynamic postural control (balance), and gait patterns in people with movement disorders [12]. However, further studies are needed to continue to validate the accuracy and reliability of accelerometric mobile devices. Furthermore, there is a need to validate the accuracy and reliability of smart phone applications utilizing accelerometry. Study 1 sought to answer the following questions:

1. Are there differences in balance, as measured by the iPod device, based on number of trials?
2. Are there differences in balance, as measured by the iPod device, based on condition?

3. What limitations exist for the software in determining balance?

Study 2 sought to answer the following questions:

1. How does the iPod application compare to industry standard instrumentation in measuring balance?
2. Do measurements vary as a function of stance condition or foam condition?

The purpose of this study was to compare the balance assessment measures from a mobile device application (iPod) utilizing accelerometric motion sensors against the balance assessment measures of a clinically valid and reliable balance platform (BIODEX Balance System SD). It was hypothesized for Study 1 that (1) all measures will be greater than the baseline of standing with the feet together and eyes closed, and (2) that the more unstable the assessment, the greater the instability compared to the baseline of standing with the feet together with eyes closed. It was hypothesized for Study 2 that (1) scores for the same measures on the BIODEX Balance System SD compared to the iPod Concussion Manager Smartphone Application will not be significantly different, and (2) the more unstable the assessment, the higher the balance score compared to the baseline or standing with feet together with eyes closed, without foam.

1.3 Significance of the Study

Since there are limited studies that incorporate the use of mobile accelerometric devices to assess balance, this study is significant by creating a foundation for developing improved methods of assessing postural stability within the advancing area of telecommunications. Also, the information obtained from this study will be of benefit to medical professionals, coaches, parents, and the athletic community, because it has the potential to report an outcome that would be beneficial to the general public and have a significant contribution to the scientific body of knowledge.

1.4 Limitations of the Study

Mobile devices that are cost-efficient and reliable and can provide accurate, quantitative data on an individual's balance could revolutionize the way people are assessed, assisted, trained, and diagnosed. This application would provide a convenient, easy way to address issues that can lead to more serious conditions and/or prevent issue from occurring.

Though assessing balance with the use of a mobile accelerometric device has many benefits, there are limitations to this study. The first limitation is the population used in the study. Although this study was designed to gather data about the effectiveness of assessing the postural sway of individuals, the population was not diverse enough that the results can be generalized to other populations to whom this application is intended. The average age of the participants was 24 years old, most of whom were healthy and active. This does not transfer well to the aging or diseased populations that may utilize this application. Another limitation is the difference in recording postural sway between the BIODEX Balance System SD and the Concussion Manager Smartphone Application. Both systems record sway, but the BIODEX Balance System SD uses strain gauges in a platform that primarily measures ankle movement, while the application takes advantage of the accelerometers and measures movement above the participant's center of gravity by having the device at the sternum of the chest. A third limitation is the cultural or social factors that may influence the knowledge or acceptance of technology and its use in health care. If the participant and/or test administrator is unfamiliar or uncomfortable with the current technology used for this study (specifically the iPod), it may cause frustration or anxiety that could potentially affect the results of this study. It is important to note because the success of this study is reliant upon the acceptance and use of current technology. In order for the application to be widely utilized, the practitioner must have knowledge of the current technology and implement it into his or her repertoire.

1.5 Delimitations of the Study

Delimitations of the study are as follows:

1. The study is delimited to undergraduate students in the Human Performance Studies Department at Wichita State University, Wichita, Kansas.
2. A delimitation of this study is the use of the Apple iPod instead of any other mobile accelerometric device.
3. A delimitation of this study is the use of the BIODEX Balance System SD force platform instead of any other reliable balance assessment tools.

1.6 Assumptions of the Study

Assumptions for this study are as follows:

1. It is assumed for this study that all participants are free of any condition or injury of the skeletal system, nervous system, muscular system or brain that would affect their balance, giving inaccurate results.
2. It is assumed that all participants attempted each trial to the best of their ability, providing accurate results for each trial.

1.7 Definition of Terms

Accelerometer: Device consisting of a moveable bar suspended on micro-machined springs that provide resistance against acceleration that measure both static and dynamic acceleration [13].

Balance: the ability to maintain the center of body mass (COM) within limits of stability determined largely by the base of support, regardless if the base is stationary or moving [1, 14-17].

Center of Mass (COM): center of gravity.

Center of Pressure (CP): pressure exerted on a supporting surface.

Degree of Tilt: Variance from center, and degrees of deflection over time at various stability levels a [2, 18]

Dynamic balance: measuring direction and magnitude of weight shift through total vertical force vectors [15, 19, 20].

Force platform: systems that measure the vertical ground reaction force and provide a means of computing the center of pressure (CP) by measuring vertical force vector projected onto a horizontal plane while standing quietly on a flat, transducer instrumented platform [21, 22].

Golgi Tendon Organ (GTO): located at the muscle-tendon interface; sensitive to slight changes in tension and is responsive to tension that occurs either by active contraction or by passive stretch resulting in decreased tension within the muscle and tendon [23].

Jerk: describes the changes of body accelerations, independently from the sensor orientation or any estimates for gravitational acceleration [24].

Muscle spindles: stretch-sensitive mechanoreceptors that provide the nervous system with information about the muscle's length and velocity of contraction, contributing to an individual's ability to discern joint movement and joint position sense [23].

Myotatic reflex: Muscle contraction in response to a muscle being stretched due to afferent fibers form the muscle spindle entering the central nervous system (CNS), dividing into branches, and taking several different paths with one path directly stimulating motor neurons going back to the muscle that was stretched [2].

Static balance (quiet standing): equilibrium is maintained for one stationary body position during continuous transfer (correction) of the center of gravity [15, 19, 20].

Vestibulo-ocular reflex: When the head is suddenly tilted, signals from the semicircular canals cause the eyes to rotate in an equal and opposite direction to rotate the head [2].

CHAPTER 2

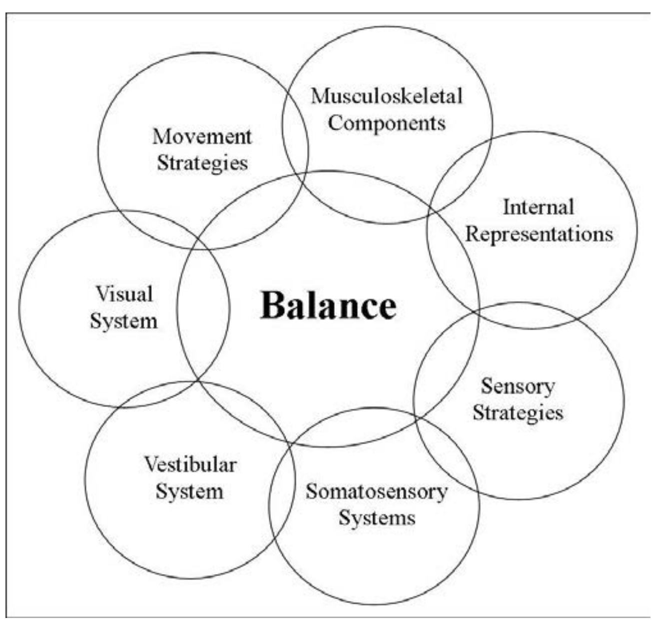
REVIEW OF THE LITERATURE

2.1 Balance

Balance is a key component of motor skills, ranging from maintaining posture to executing complex sport skills, and is defined as the ability to maintain the center of body mass (COM) within limits of stability determined largely by the base of support, regardless if the base is stationary or moving [1, 14-17]. It is a complex process involving coordination of multiple sensory, motor, and biomechanical components, and can be modified or effected by the task being performed, features of the environment, and/or the body's movement, sway, and biomechanics [1-4]. Figure 2.1 shows the conceptual model for the balance system theory, including the interacting systems contributing to balance and orientation [1, 25, 26].

FIGURE 2.1

A CONCEPTUAL MODEL REPRESENTING THE INTERACTING SYSTEM CONTRIBUTING TO TASK SPECIFIC BALANCE AND ORIENTATION



The functional goals of the balance system includes: (1) maintenance of a specific postural alignment, such as sitting or standing, (2) facilitation of voluntary movement, such as the movement transitions between postures, and (3) reactions that recover equilibrium to external disturbances, such as a trip, slip, or push [5].

2.2 Types of Balance

Balance uses sensory information in the form of vestibular, visual, and tactile-proprioceptive inputs that is processed by neural structures, which in turn produce an organized motor response that reflexively restores body alignment [27, 28]. Balance can be categorized into two types: static and dynamic. Static balance is when equilibrium is maintained for one stationary body position (quiet standing) during continuous transfer (correction) of the center of gravity, while dynamic balance refers to measuring direction and magnitude of weight shift through total vertical force vectors [15, 19, 20]. Both static and dynamic balance require integrating sensory information from the visual, vestibular, and somatosensory systems [15]. This system operates as a feedback control circuit between the brain and the musculoskeletal system by detecting instability and responding to the motion of linear and angular accelerations and muscle stretch at the ankle, knee and trunk joints [2, 29, 30]. The feedback obtained from the vestibular, visual, and proprioceptive (or somatosensory) sensors relays commands to the muscles of the extremities which then generate an appropriate contraction to maintain postural stability [31, 32].

2.3 Physiological Feedback Influencing Balance

Each feedback sensor plays an important role in maintaining balance. The vestibular apparatus can be used in three different ways. There are three ways the apparatus can be used. First, the information is used to control eye muscles so that when the head changes position, the eyes can stay fixed on one point [2]. Second, vestibular information can be used to maintain upright posture [2]. A third use of vestibular information involves conscious awareness of the body's position and acceleration after information has been relayed to the cortex by the thalamus [2]. When sudden changes or perturbations are induced causing a person to change his or her direction of movement or head position (i.e., leaning the head sideways, forward, or backward), the automatic control mechanisms provided by vestibular input becomes crucial for stabilizing the direction of gaze and ultimately one's equilibrium [2].

Vision is an important contributor to balance, especially under conditions of postural perturbation. When the head is suddenly tilted, signals from the semicircular canals cause the eyes to rotate in an equal and opposite direction to rotate the head, which is called the vestibulo-ocular reflex [2]. The vestibular apparatus contributes to posture by maintaining reflexes associated with keeping the head and neck in the vertical position and allowing the vestibulo-ocular reflex to control eye movement [2].

The proprioceptive system functions via the mechanoreceptive senses of touch, pressure, and vibration, all of which are commonly referred to as the tactile senses, and the sense of position, which determines the relative positions and rates of movement of parts of the body [2]. Sensory mechanoreceptors play a vital role in the nervous system's control of posture. Those mechanoreceptors are called muscle spindles and Golgi tendon organs. Muscle spindles are stretch-sensitive mechanoreceptors that provide the nervous system with information about the muscle's length and velocity of contraction, contributing to an individual's ability to discern joint movement and joint position sense [23]. Muscle spindles play an important role in providing afferent feedback that translates to appropriate reflexive and voluntary movement [33-35].

When afferent fibers form the muscle spindle enter the central nervous system (CNS), they divide into branches, and take several different paths; one path directly stimulates motor neurons going back to the muscle that was stretched, thereby completing a reflex arc (called the stretch or myotatic reflex), that causes a muscle contraction in response to a muscle being stretched [2]. The GTO is located at the muscle-tendon interface and relays afferent information about tensile forces within the tendon [23]. The GTO is sensitive to slight changes in tension and is responsive to tension that occurs either by active contraction or by passive stretch [23]. The activation of the GTO results in Ib afferent neuron activation, which synapses in the spinal cord on interneuron that are inhibitory to the alpha motor neuron of the associated muscle, resulting in decreased tension within the muscle and tendon [23].

Ankle rotation is the most probable stimulus of myotatic reflex, appearing to be first useful phase of activity in the leg muscle both prior to movement as well as after a change in erect position occurs and correction is needed [36] . The myotatic reflex occurs when perturbations posture automatically evoke functionally directed responses in the leg muscles to compensate for imbalance or increased postural sway [36, 37]. When posture moves forwards or backwards from the COM, gravity acts down vertically and exerts a small net torque on the ankle, imposing a rotation of the ankle resulting a postural lean [38]. Muscle spindles sense a stretching of the agonist, thus sending information along its afferent fibers to the spinal cord where the information is transferred to alpha and gamma motor neurons that carry information back to the muscle fibers and muscle spindle, respectively, and contract the muscle to prevent or control additional postural sway [37]. The ankle strategy is found when the perturbation is small and the support surface is firm, and predicts that the ankle plantarflexors/dorsiflexors alone act to control postural lean [38, 39]. In more perturbed situations or when the ankle cannot act, a hip strategy responds to flex the hip, thus moving the COM posteriorly, or to extend the hip to move the COM anteriorly [39]. The hip strategy is observed when the perturbations are rapid and larger and the support structure is compliant or smaller than the feet [38].

2.4 Methods of Assessment of Balance

Balance assessment is vital for accurately determining an individual's postural stability and/or lack thereof. In order to evaluate postural stability, standard, reliable assessments were developed to provide valid and reproducible results. Table 2.1 shows the relevant studies examining reliability of clinic measurements of balance [40].

TABLE 2.1

STUDIES EXAMINING RELIABLITY OF CLINICAL MEASUREMENTS OF BALANCE

Clinical Balance Test	**Outcome Measure**	**Test-retest Reliability**	**Inter-rater Reliability**	**Validity**
Static unipedal stance (eyes open)	Maximum time maintained	Atwater(1990): (r=0.91) Balogun (1992): (ICC=0.95) Stones (1987): (r=0.68	Atwater (1990): (r=0.96)	Nil
Static unipedal stance (eyes closed)	Maximum time maintained	Atwater (1990): (r=0.59-0.77) Balogun (1992): (ICC=0.95) Bohannon (1993): (ICC=0.44-0.75) Stones (1987): (r=0.68)	Atwater(1990): (r=0.96)	Ekdahl (1989): (r=-0.31- -0.42) Stabilometry sway path measurements (length, velocity, area)
	Error scoring system	Riemann (1999): (F(1.10)=0.71) p=0.5031	Riemann (1999): (ICC=0.93)	Riemann (1999): (r=0.42) Stabilometry sway path measurements (area)

ICC = Intertester Intraclass Correlations, r = correlation coefficient, F = probability distribution

TABLE 2.1 (continued)

Clinical Balance Test	**Outcome Measure**	**Test-retest Reliability**	**Inter-rater Reliability**	**Validity**
Dynamic bipedal stance tiltboard tests (eyes open)	Error scoring system	Atwater (1990): (r=0.45)	Atwater (1990): (r=0.96-1.0)	Nil
	Angle of tilt (major postural)	Broadstone (1993): (ICC= 0.49-0.54)	Nil	
	Error scoring system		Mattacola (1997): (ICC=0.91-0.92)	
Dynamic stance using foam surface	Error scoring system (bipedal)	Deitz (1991): (r=0.05-0.83)	Crowe (1991): (r=0.82-0.92)	
	Error scoring system (unipedal)	Riemann (1999): F(1.10)=1.08	Riemann (1999): (ICC=0.92)	Riemann (1999): (r=0.79) Stabilometry sway path measurements (area)
Functional reach test	Maximum lateral distance reached maintaining balance (cm)	Brauer (1999): (ICC=0.99)	Nil	Nil
	Maximum anterior distance reached maintaining balance (cm)	Donahoe (1994): (ICC=0.83)	Donahoe (1994): (ICC=0.98	
		Mackenzie (1999): (ICC=0.79)		
Multiple single-leg hop stabilization test on numbered floor pattern	Scoring system for balance and landing errors	Riemann (1999): (F(2.28)=4.32 p=0.023	Riemann (1999): (ICC=0.92)	Nil

ICC = Intertester Intraclass Correlations, r = correlation coefficient, F = probability distribution

Many tests have been developed for measurements of standing balance. A simple unipedal static balance test is widely used and validated method to measure standing balance [41]. An example of a unipedal static stance is the one-leg standing balance test. The one-leg standing test is a time measured test where an individual stands on one leg with eyes closed, the other leg slightly flexed, and each hand held on the opposite shoulder [41]. For measurement during a dynamic balancing situation, a multiple direction stabilization test is commonly administered [42]. An example of this is the Start Excursion Balance Test (SEBT). The SEBT involves having a participant maintain a base of support with one leg while maximally reaching in different directions with the opposite leg [43]. Other tools, such as foam and tilt-boards, have been used to alter the proprioceptive feedback of the support surface in assessing dynamic balance [42, 44]. Functional reach tests have been used in children and the elderly to examine dynamic balance, not by an external force, but rather a self motivated reach [45]. An example is the Multi-Directional Reach Test (MDRT), in which the participant, standing on both feet, reaches as far as possible without taking a step towards an end distance marked by a yard stick [45].

There are other functional tests used to measure balance, posture, and equilibrium, typically in the elderly and neurologically impaired population. These tests are the Berg Balance Test, the Postural Assessment Scale for Stroke patients, and the Continuous-Scale Physical Functional Performance Test [6-9]. The Berg Balance Test has fourteen categories in which the participant is tested on and scored, such as sitting to standing and standing on one foot, to determine if the participant has enough stability to walk independently [6]. The Postural Assessment Scale for Stroke patients (PASS) contains twelve, four-level items of varying difficultly for assessing the ability of a patient to maintain or change posture [8]. The Continuous-Scale Physical Functional Performance Test (CS-PFP) measures functional capability of tasks typically required for independent living, and are rated based on scores from five domains: upper body strength, upper body flexibility, lower body strength, balance and coordination, and endurance [9].

Other functional balance assessments have been developed for the use of determining postural stability after balance disturbance takes place, such as traumatic brain injuries like concussions. The Sport Concussion Assessment Tool-version 2 (SCAT2) is a nuerocognitive tool that was developed for patient education in addition to physician assessment in individuals who have sustained a sports related concussion, and consists of both subjective and evaluation portions [11]. The subjective portion consists of 25 symptoms that the athlete rates based on how they feel at the time of administration on a seven-point scale of 0-6, with 0 representing no symptoms and 6 representing severe symptoms [11]. The evaluation portion of the SCAT2 includes signs, modified Maddocks questions (quick, simple questions to screen players for sports concussion, such as "which team do you play for?), symptom score, a cognitive assessment and neurological screening [11]. The cognitive assessment includes recall of five unrelated words immediately upon hearing them (immediate word recall) and again following concentration tasks (delayed word recall), stating the months of the year in reverse order, and repeating single digits in reverse order [11]. Knowledge of an individual's score on a measure when not injured provides a baseline normative value for that specific individual for comparison at the time of injury [11]. The Balance Error Scoring System (BESS) was developed as an objective sideline assessment tool for the evaluation of postural-stability deficits after concussion [46, 47]. The BESS consists of 3 stances: double-leg stance (hands on the hips and feet together), single-leg stance (standing on the non-dominant leg with hands on hips), and a tandem stance (non-dominant foot behind the dominant foot) in a heel-to-toe fashion [10, 46, 47]. The stances are performed on a firm surface and on a foam surface with the eyes closed, with errors counted during each 20-second trial [10, 46, 47]. An error is defined as opening eyes, lifting hands off hips, stepping, stumbling or falling out of position, lifting the forefoot or heel, abducting the hip by more that 30^{o} or failing to return to the test position in more than 5 seconds [10, 46, 47]. In comparison to other balance assessments, several studies show that the BESS has moderate (<0.75) to good (>0.75) reliability and moderate to high criterion-related validity [10]. The BESS has high content validity in identifying balance deficits in concussed and fatigued populations, functional ankle instability, ankle bracing, aging populations, and those completing neuromuscular training[46, 48-57]. The BESS is a clinical evaluation that correlates with laboratory-based measures for criterion-related validity and construct validity [10].

Though several of these methods of balance assessment have been used in the clinical setting, many have been criticized for offering only subjective information rather than objective information. Traditional methods of technology have provided the medical community with quantitative methods of assessing both static and dynamic balance [2]. These systems provide an easy and practical method of quantitatively assessing functional balance through analysis of postural sway [2]. These systems are called force platforms. Force platform systems measure the vertical ground reaction force and provide a means of computing the center of pressure (CP) by measuring vertical force vector projected onto a horizontal plane while standing quietly on a flat, transducer instrumented platform [21, 22]. The measurement determines where the average center of pressure or center or force is located and how much variability of this location occurs [21, 22]. Increased postural sway indicates greater effort to stand in a stationary position and thus provoke balance [21]. Force platforms evaluate four aspects of postural control: steadiness (the ability to keep the body as motionless as possible), Symmetry, (the ability to distribute weight evenly between the two feet in an upright stance), dynamic stability, (the ability to transfer the vertical projection of the center of gravity around a stationary supporting base), and dynamic balance (the measurement of postural responses to external perturbations from a platform moving in one of four directions- tilting toes up, tilting toes down, medial-lateral, and anterior-posterior) [21, 58].

Another method adopted by developers has been the use of multiple strain gauges. Strain gauges, such as the BIODEX Balance System SD (BBS) (BIODEX Medical Systems, Shirley, NY) uses a circular platform that is free to move about the anterior-posterior (AP) and medial-lateral (ML) axes simultaneously [18, 22]. In addition, it is possible to vary the stability of the platform by varying the resistance force applied to the platform through springs on the underside of the platform [18]. Rather than measuring the deviation of the CP during static conditions, the BBS measures the degree of tilt (variance from center, and degrees of deflection over time at various stability levels) about each axis during dynamic conditions, providing more specific information on the ankle joint mechanoreceptors that offer proprioceptive feedback necessary for balance control [2, 18]. From the degrees of tilt about the AP and ML axes, the BBS calculates the medial-lateral stability index (MLSI), the anterior-posterior stability index (APSI), and the overall stability index (OSI) [59, 60]. Figure 2.2 expresses the formulas for calculating the APSI, MLSI, and OSI.

FIGURE 2.2

FORMULAS FOR CALCULATING THE ANTERIOR-POSTERIOR STABILITY INDEX (APSI), MEDIAL-LATERAL STABILITY INDEX (MLSI), AND OVERALL STABILITY INDEX (OSI) FOR THE BIODEX BALANCE SYSTEM SD

$$\text{APSI} = \sqrt{\frac{\sum(0 - Y)^2}{\#\ \text{samples}}}$$

$$\text{MLSI} = \sqrt{\frac{\sum(0 - X)^2}{\#\ \text{samples}}}$$

$$\text{0SI} = \sqrt{\frac{\sum(0 - Y)^2 + \sum(0 - X)^2}{\#\ \text{samples}}}$$

According to the BIODEX Clinical Resource Manual (1999), the OSI represents the variance of foot platform displacement in degrees from level, in all motions during a test. A high Stability Index is indicative of a subject having difficulty maintaining a level platform position and may represent poor neuromuscular control [22]. Zero (0) represents a starting point for a perfectly balanced state or, center of balance, and the displacement for each variance is subtracted from zero [22]. The variance "Y" corresponds to the Anterior/Posterior Stability Index (APSI), and represents the variance of foot platform displacement in degrees, from level, for motion in the sagittal plane [22]. A high APSI score in this direction may indicate poor neuromuscular control of (1) the Quadriceps and/or Hamstring muscles and (2) the Anterior/Posterior compartment muscles of the lower leg [22]. The variance "X" corresponds to the Medial/Lateral Stability Index (MLSI), and represents the variance of foot platform displacement in degrees, from level, for motion in the frontal plane [22]. A high MLSI score in this direction may be indicative of poor neuromuscular control of the inversion or eversion muscles of the lower leg, both bilaterally and unilaterally [22]. The MLSI and the APSI assess the fluctuations from horizontal along the AP and ML axes of the BBS, respectively, while in contrast, the OSI is a composite of the MLSI and APSI, and is sensitive to changes in both directions [18].

Studies show that the BBS is highly reliable to evaluate dynamic postural balance, and that the test-retest reliability of the produced stability index is acceptable for clinical testing and is comparable to other balance measures currently in use [59-62]. Table 2.2 shows the recent studies conducted to examine and test the validity and reliability of the BBS [18, 59, 60, 62, 63].

TABLE 2.2

STUDIES CONDUCTED TO TEST VALIDITY AND RELIABLITY OF THE BIODEX BALANCE SYSTEM SD

Author, Year	**Reliability Assessment**	**Population**	**Study Design**	**Results**	**Reliability/ Validity**
Karimi et al., (2008)	n/a	23 male patients with low-back pain (age 30.4±6.5 yr) 20 healthy m (age 29.8±6.4 yr)	Cross-sectional non- experimental design MLSI, APSI, OSI were measured; bilateral and unilateral stance with eyes open and eyes closed, 20-s	Healthy: (ICC=0.91-0.95) Low-back Pain: (ICC=0.88-0.96)	High reliability to evaluate dynamic postural balance in subjects with and without low-back pain
Blackburn et al., (2003)	Intertester & intratester reliability	7 male, 7 female healthy subjects, injury free (age 21±2 yr)	Trunk flexion/extension, trunk lateral flexion, right and left hip flexion/extension and abduction/adduction angular position variances were assessed in using an electromagnetic tracking system during bilateral stance on firm, foam, and multiaxial support surfaces with and without vision	ICC for firm surface, eyes open=0.31; results revealed no significant differences in the quantity of motion occurring at the hips and trunk during quiet, bilateral stance on firm, foam, and multiaxial support surfaces, both in the presence and absence of visual input	ICC values suggests moderate to high reliability

w = women, m = men, yr = years old, -s = seconds ICC = Intertester Intraclass Correlations,
APSI = Anterior Posterior Stability Index, MLSI = Medial Lateral Stability Index, OSI = Overall Stability Index

TABLE 2.2 (continued)

Author, Year	Reliability Assessment	Population	Study Design	Results	Reliability/ Validity
Hinman, (2000)	Test-retest reliability	Study 1: 31 w, 19 m (age 32.9±11.5yr) Study 2: 37 women,13 men (age 28.1±8.1 yr) Study 3: 47 w, 13 m (age 71.4±5.4 yr) Study 4: 37 w, 7 m (age 26±6 yr)	Study 1: two 30-s tests, at 2 different stability levels (3 & 6) with eyes open, looking straight ahead Study 2: OSI was compared between eyes open looking straight ahead, eyes open receiving visual feedback, & eyes closed, 30-s Study 3: subjects tested both with hard-soled & soft-soled shoes, eyes open at level 7, receiving visual feedback, 30-s Study 4: subjects moved the platform in various directions by leaning as far as possible, 30-s	ICC for static tests=0.44-0.89; ICC for LOS=0.77-0.89	Test-retest reliability of the stability index is acceptable for clinical testing and is comparable to other balance measures
Arnold et al,, (1998)		8 m 11 w, healthy (age 24.4±4.2 yr)	Non-experimental and quasi-experimental methods MLSI, APSI, OSI, & time-in-balance scores were recorded, 30-s tests using 8 resistances	Multiple regression= APSI & MLSI significantly contributed to OSI, with APSI accounting for 95% of OSI variance	Clinicians may find it useful to use APSI and MLSI separately to assess balance
Schmitz & Arnold, (1998)	Intertester & intratester reliability	8 m 11 w, healthy, (age 24.4±4.2 yr)	5 30-s balance tests, with platform stability decreasing over the 30-s	(ICC=0.70-0.42) for stability and (ICC=0.93-0.54) for foot placement; OSI for intertester=0.82, OSI for intratester=0.70	Reliable within clinical ranges

w = women, m = men, yr = years old, -s = seconds ICC = Intertester Intraclass Correlations,
APSI = Anterior Posterior Stability Index, MLSI = Medial Lateral Stability Index, OSI = Overall Stability Index

2.5 Accelerometry

Recent technological advancements in electronics and telecommunications have provided even more accessible quantitative methods of assessing both static and dynamic balance through accelerometers in mobile devices, specifically, smartphones. Accelerometers were proposed in the 1950's, and have evolved technologically to provide sufficient quality and reliability with tandem characteristics of high volume and low-cost production and allow for the quantitative and portable assessment of human locomotion and movement disorders [64]. Accelerometers measure both static and dynamic acceleration, consisting of a moveable bar suspended on micro-machined springs that provide resistance against acceleration [13]. Deflection of this bar is then converted into an acceleration reading (G-forces) [13]. Three accelerometers can be incorporated into a single device providing information on three-dimensional movement (tri-axial accelerometer) [13]. Accelerometers are an ideal choice for evaluating variability of movement and balance providing a non-invasive, portable method of measurement [65, 66]. Balance evaluation using accelerometers has been compared with comprehensive clinical balance assessments (such as Romberg's test, heel-toe straight line walking, and functional reach test) in healthy older subjects and idiopathic fallers [67, 68]. In another study, the gait in older adults with and without stability problems and young subjects was compared using trunk accelerometers.[67, 68]. Both of these studies suggest that accelerometers are useful for assessing balance and that they detect definite abnormalities in the gait of fallers [67, 68]. A selection of balance accelerometric studies that have used custom designed systems are presented in Table 2.3 [12].

TABLE 2.3

A SELECTION OF BALANCE STUDIES USING CUSTOM DESIGNED

ACCELEROMETERIC SYSTEMS

Study and Year		Focus of Study	Dependent Variables
Breniere and Dietrich	(1992)	Upper body motion immediately before and after gaitinitiation	3D hip and shoulder accelerations
Bussmann et al.	(2004)	Physical strain assessment during prosthetic gait	2D upper trunk and 1D thigh accelerations
Giansanti	(2006)	Body segment inclination	3D lower trunk acceleration and angular velocity
Jasiewicz et al.	(2006)	Heel contact and toe off events	Foot and shank 3D accelerations, and angular velocity
Kavanagh et al.	(2006)	Postural control and stability during walking	3D upper body and shank accelerations
Lyons et al.	(2005)	Body segment inclination, mobility monitoring	2D trunk and thigh accelerations
Mansfield et al.	(2003)	Heel contact events	2D lower trunk accelerations
Manson et al.	(2000)	Ambulatory dyskinesia monitor	3D shoulder accelerations
Menz et al.	(2003)	Postural control and stability during walking	3D upper body accelerations
Moe-Nilssen	(1998)	Postural control and stability	3D lower trunk accelerations
Petrofsky et al.	(2005)	Amplitude of segmental motion	2D upper and lower body accelerations
Prill and Fahrenberg	(2006)	Posture and periodic limb movements	3D upper trunk and 1D thigh and shank accelerations
Sekine et al.	(2000)	Classification of walking patterns	3D lower trunk acceleration
Selles et al.	(2005)	Heel contact and toe off events	2D shank accelerations
Schutz et al.	(2002)	Mobility monitor	1D lower trunk accelerations
Simcox et al.	(2005)	Body segment orientation, mobility monitoring	Upper and lower body 3D accelerations, and angular velocity
Tanaka et al.	(2004)	Body segment orientation, mobility monitoring, gait velocity	Upper and lower body 3D accelerations, and angular velocity
Willemsen et al.	(1990)	Knee joint angle	1D thigh and shank accelerations
Willemsen et al.	(1990)	Automatic swing and stance phase detection	1D shank accelerations
Zijlstra	(2004)	Spatiotemporal gait parameters such as stride duration, step length and gait velocity	3D lower trunk accelerations

2.6 The Need for Validation of Accelerometry in Balance Assessment

Though there is limited information on the validity and reliability of accelerometers as tools for balance assessment, the current literature indicates that accelerometry can provide accurate and reliable measures of basic temporospatial gait parameters, shock attenuation, and segmental accelerations of the body when walking, thereby providing useful insights into the motor control of normal walking, age-related differences in dynamic postural control (balance), an gait patterns in people with movement disorders [12]. Based on current research, the use of accelerometers in smart phones is increasingly advancing [64]. The concept of a wireless accelerometer system for quantifying the attributes of gait and balance have been illustrated through the G-link® Wireless Accelerometer Node and Apple iPod and iPhone [64, 69-75]. The iPod and iPhone developed by Apple are comprised of a three dimensional accelerometer, and have the capacity to store quantification data samples, which can be conveyed wirelessly through email to a remote location for post-processing.

The most recent mobile device applications for assessing balance analyze jerk- the change of accelerations- instead of accelerations themselves [24]. The magnitude of jerk describes the changes of body accelerations, independently from the sensor orientation or any estimates for gravitational acceleration [24]. Given two consecutive accelerations, the difference vector can be calculated, which corresponds to the average jerk in time interval [24]. Assuming that the orientation has not changed in this time interval, the gravitational component is the same in both time steps, and they are cancelled out, giving the difference of body accelerations without knowing gravitational acceleration [24]. In addition, the magnitude of difference vector is orientation-independent, and thus accurate [24]. Analyzing jerk also reveals the angle of direction change [24].

Studies show that the iPod and iPhone demonstrate the capacity to accurately acquire quantified balance parameters with a sufficient level of consistency [69, 70, 74, 75]. However, further studies are needed to continue to validate the accuracy and reliability of accelerometric mobile devices. Furthermore, there is a need to validate the accuracy and reliability of smart phone applications utilizing accelerometry. The purpose of this study was to compare the balance assessment measures from a mobile device application (iPod) utilizing accelerometric motion sensors against the balance assessment measures of a clinically valid and reliable balance platform (BIODEX Balance System SD). Study 1 sought to answer the following questions:

1. Are there differences in balance, as measured by the iPod device, based on number of trials?
2. Are there differences in balance, as measured by the iPod device, based on condition?
3. What limitations exist for the software in determining balance?

Study 2 sought to answer the following questions:

1. How does the iPod application compare to industry standard instrumentation in measuring balance?
2. Do measurements vary as a function of stance condition or foam condition?

It was hypothesized for Study 1 that (1) all measures will be greater than the baseline of standing with the feet together and eyes closed, and (2) that the more unstable the assessment, the greater the instability compared to the baseline of standing with the feet together with eyes closed. It was hypothesized for Study 2 that (1) scores for the same measures on the BIODEX Balance System SD compared to the iPod Concussion Manager Smartphone Application will not be significantly different, and (2) the more unstable the assessment, the higher the balance score compared to the baseline or standing with feet together with eyes closed, without foam.

CHAPTER 3

METHODOLOGY

This chapter describes the methods and data used to address the research questions presented in this study. Discussion in this chapter includes: (1) restatement of the research questions answered by the study, (2) description of the site and participant selection process, (3) explanation of the instruments and measures used for data collection, (4) discussion of the study procedures, (5) description of data analysis used, and (6) assurances regarding the protection of human subjects.

3.1 Research Questions

Studies have shown that assessment of balance can contribute to improvement and implementation of programs that can prevent and assist in diagnosing injury and disease, assess the neuromuscular effects and decrease the risk of falling in the aging, provide rehabilitation, determine neurological disorders, enhance functional or athletic performance, and provide an overall better understanding of the physiological systems contributing to postural movement and stability [1, 3, 10, 14, 17, 20, 25-30, 37, 46, 47, 76-87]. Though many balance assessment tools are being utilized, the most accessible and cost-efficient methods, though adequate, rely on subjective and qualitative measures that the test administrator observes and concludes based on his or her opinion. This study determines the validity and reliability of an accelerometric mobile device balance application to fulfill the need for accessible and cost-efficient quantitative measures of balance that provide precise, comparative data with each subject. Study 1 sought to answer the following questions:

1. Are there differences in balance, as measured by the iPod device, based on number of trials?
2. Are there differences in balance, as measured by the iPod device, based on condition?
3. What limitations exist for the software in determining balance?

Study 2 sought to answer the following questions:

1. How does the iPod application compare to industry standard instrumentation in measuring balance?
2. Do measurements vary as a function of stance condition or foam condition?

3.2 Site and Participation Selection

This study was conducted at Wichita State University (WSU) in Wichita, Kansas. Baseline measures were assessed in a laboratory setting and all balance assessments were conducted within the same laboratory. The selection of this site for the study was chosen for three main reasons: (1) access to necessary equipment for study procedures, (2) time constraints regarding room availability, and (3) convenience of the location for participant use.

Since the study utilized the BIODEX Balance System SD and Apple iPods, the site selected for conducting each trial had to be in a location that was accessible to the BBS, and in a location that the test administrators could keep account of the Apple iPods utilized for the trials. The location for the study had to be a familiar, convenient location for all participants in order to prevent location from being a limiting factor.

3.2.1 Participants

Due to the nature of the study, the time available for the study, and the logistical constraints of the study, convenience sampling was used. While convenience sampling limits the extent to which results can be generalized to the populations that may benefit from mobile balance assessment, convenience sampling is useful for validation and reliability studies on the probability of interventions for use in future research.

The participants of this study were undergraduate student volunteers at WSU. Seventy-five participants (38 female, 37 male), age ranging from 19 to 60 years (median=22; age 24.3±6.8 yrs), were recruited from undergraduate courses in the Human Performance Studies Department of WSU. Each participant gave written and verbal consent before participating in the study.

3.3 Instruments and Measures

Discussion of the instruments and measures used during this study include (1) the BIODEX Balance System SD, (2) the Concussion Manager Smartphone Application, and (3) the Thera-Band® Stability Trainer (foam). All device configurations, settings, and usage were in accordance with each device's manufacturer instructions for proper set up, use, and care of the equipment.

3.3.1 BIODEX Balance System SD

The BIODEX Balance System SD (BBS) (BIODEX Medical Systems, Shirley, NY) uses a circular platform that is free to move about the anterior-posterior (AP) and medial-lateral (ML) axes simultaneously [18, 22]. In addition, it is possible to vary the stability of the platform by varying the resistance force applied to the platform through springs (strain gauges) on the underside of the platform [18]. Rather than measuring the deviation of the center of pressure during static conditions, the BBS measures the degree of tilt (variance from center, and degrees of deflection over time at various stability levels) about each axis during dynamic conditions, providing more specific information on the ankle joint mechanoreceptors that offer proprioceptive feedback necessary for balance control [2, 18]. From the degrees of tilt about the AP and ML axes, the BBS calculates the medial-lateral stability index (MLSI), the anterior-posterior stability index (APSI), and the overall stability index (OSI) [59, 60]. The BBS also has a standardized indexed foam pad that matches the size of the Balance SD platform, and was used in this study.

3.3.2 Concussion Manager Smartphone Application

The Concussion Manager Smartphone Application was developed by Capacity Sports (Tulsa, OK) and is designed as a tool to measure balance. It can be used in clinical, athletic, or typical everyday settings, with the goal of providing accurate, quantitative information about the user, to help assess and verify balance and/or determine conditions preventing proper balance, such as traumatic brain injuries like concussions. The application takes advantage of the accelerometers found in mobile devices, like Apple iPods or iPhones. Accelerometers measure both static and dynamic acceleration, consisting of a moveable bar suspended on micro-machined springs that provide resistance against acceleration [13]. Deflection of this bar is then converted into a into an acceleration reading [13]. Three accelerometers can be incorporated into a single device providing information on three-dimensional movement (tri-axial accelerometer) [13]. The information measured is the anterior/posterior and medial/lateral stability, which is the displacement in degrees from level. Accelerometers are an ideal choice for evaluating variability of movement and balance providing a non-invasive, portable method of measurement [65, 66].

3.3.3 Thera-Band® Stability Trainer

Thera-Band® (Hygenic Corp., Akron, OH) Stability trainers are oval-shaped foam pads to use for balance training. According to the Thera-Band® website, the Stability Trainers are closed cell foam pads with an anti-slip ridged surface and oval foot fitting shape. The foam pads are effective for balance training in older adults, rehabilitation of lower extremities, and for sports performance enhancement. Made of durable PVC, the extra soft Stability Trainer's heavy gauge side walls resist the tendency to roll the ankle during exercise. Additionally, it offers two options for use: one surface with rounded points providing tactile inputs for sensorimotor training; and the opposite surface with an anti-skid bars that resist slipping. For this study, the Blue foam (described as "soft", 16" x 9" x 2") was used for ground trials requiring use of a foam pad.

3.4 Procedures

Upon enrollment into the study, participants completed the Informed Consent form detailing the outline of the study's trials. Following the completion of the Informed Consent, participants' height and weight were measured for correct calibration of the BBS and Concussion Manager Smartphone Application. Participants' age, gender, and dominant foot were recorded as well. Once all personal data was collected, familiarization with the technology and each participant was instructed on proper technique for each trial for each day of participation. Participants conducted two studies over a one-week period.

3.4.1 Study 1: iPod Trials Comparisons

In Study 1, participants completed eight balance assessments three times, using the iPod, the Concussion Manager Smartphone Application developed by Capacity Sports, and the Thera-Band® Stability Trainer. Participants were first familiarized with the Concussion Manager Smartphone Application. The Concussion Manager performs two, ten second tests before collecting data. Once the "Begin Test" button is pressed, the participant has three seconds to assume the proper position before the test begins. The application has an audible count-down tone to inform the participant when the test begins and ends. Once the test ends, the participant hands the mobile device to the test administrator, and the test administrator advances to the second test. Once the participant has the mobile device and presses "Begin Test", the participant again has three seconds to assume the proper position, and then the ten second test begins. Regardless of position, for every test, the left foot was pre-determined to be the "dominant" foot. All single-leg tests were performed on the left foot, and the left foot was in front during tandem stances. Proper posture was required for every test, which included standing in an upright, shoulders back position, with both hands on the mobile device, with the device pressed up against the center of the chest. The assessments began with feet together and eyes closed. This was used as the "baseline" measure. After the baseline, the following assessments were 1) feet together with eyes closed on foam, 2) single-leg on the ground with eyes open, 3) tandem stance on the ground with eyes open, 4) single-leg on the ground with eyes closed, 5) tandem stance on the ground with eyes closed, 6) tandem stance on foam, and finally 7) single-leg on foam. Once the participant completed the eight assessments, the participants repeated all eight assessments, rested, then repeated all eight assessments for a third time. Anterior/posterior and medial/lateral stability was recorded and was termed Actual Stability Score.

3.4.2 Study 2: iPod versus BIODEX Comparisons

During Study 2, the participants completed four balance assessments (double-leg, eyes closed, double-leg on foam with eyes closed, single-leg with eyes closed, and single-leg on foam with eyes closed), using the BIODEX Balance System SD platform and the Concussion Manager Smartphone Application at the same time. The Participants were first familiarized again with the Concussion Manager Smartphone Application. The Concussion Manager performs two, ten second tests before collecting data. Once the "Begin Test" button is pressed, the participant has three seconds to assume the proper position before the test begins. The application has an audible count-down tone to inform the participant when the test begins and ends. Once the test ends, the participant hands the mobile device to the test administrator, and the test administrator advances to the second test. Once the participant has the mobile device and presses "Begin Test", the participant again has three seconds to assume the proper position, and then the ten second test begins. Regardless of position, for every test, the left foot was pre-determined to be the "dominant" foot. All single-leg tests were performed on the left foot, and the left foot was in front during tandem stances. Proper posture was required for every test, which included standing in an upright, shoulders back position, with both hands on the mobile device, with the device pressed up against the center of the chest. Beginning the test on the mobile device had to be started simultaneously with the BBS. The participants' height, weight, and age were imputed into the system, and then positioned onto the platform indicated by the promptings on the screen of the BBS. Once the program was set, the test administrator counted down, and began the BBS test at the same time the participant pressed "Begin Test" on the Concussion Manager Application. The test administrator also gave the participants a BESS score with each trial. The Balance Error Scoring System (BESS) was developed as an objective sideline assessment tool for the evaluation of postural-stability deficits after concussion [46, 47]. An error is defined as opening eyes, lifting hands off hips, stepping, stumbling or falling out of position, lifting the forefoot or heel, abducting the hip by more that 30^o or failing to return to the test position in more than 5 seconds [10, 46, 47]. The test administrator counted each error during each of the four trials. Anterior/posterior and medial/lateral stability was recorded on both systems.

3.5 Statistical Analysis

Statistical analyses for this study were completed with the use of Statistical Packages for the Social Sciences (SPSS) version 17.0. Descriptive statistics were computed on all data. For both Study 1 and Study 2, repeated measures general linear models were computed.

3.6 Protection of Human Subjects

Approval from the Wichita State University Institutional Review Board (IRB) for Research involving Human Subjects was obtained for the study design and consent form prior to the initiation of participation recruitment and data collection. Informed consent was explained verbally and in writing for all study participants. Informed consent was obtained from all study participants and assurances were provided by the researcher that their responses or data would be reported as a group, or a representative or group data, and not identified by, or identifiable as pertaining to, a specific individual.

CHAPTER 4

RESULTS

4.1 Restatement of the Study Hypotheses

Recent technological advancements in electronics and telecommunications have provided even more accessible quantitative methods of assessing balance through accelerometers in mobile devices. Despite the increase of research in the both areas of balance assessment and telecommunications, there are limited studies that apply mobile accelerometry to human balance. From those studies, the current literature indicates that accelerometry can provide accurate and reliable measures of basic temporospatial gait parameters, shock attenuation, and segmental accelerations of the body when walking, thereby providing useful insights into the motor control of normal walking, age-related differences in dynamic postural control (balance), and gait patterns in people with movement disorders [12]. However, further studies are needed to continue to validate the accuracy and reliability of accelerometric mobile devices. Furthermore, there is a need to validate the accuracy and reliability of smart phone applications utilizing accelerometry. Study 1 sought to answer the following questions:

1. Are there differences in balance, as measured by the iPod device, based on number of trials?
2. Are there differences in balance, as measured by the iPod device, based on condition?
3. What limitations exist for the software in determining balance?

Study 2 sought to answer the following questions:

1. How does the iPod application compare to industry standard instrumentation in measuring balance?
2. Do measurements vary as a function of stance condition or foam condition?

It was hypothesized for Study 1 that (1) all measures will be greater than the baseline of standing with the feet together and eyes closed, and (2) that the more unstable the assessment, the greater the instability compared to the baseline of standing with the feet together with eyes closed. It was hypothesized for Study 2 that (1) scores for the same measures on the BIODEX Balance System SD compared to the iPod Concussion Manager Smartphone Application will not be significantly different, and (2) the more unstable the assessment, the higher the balance score compared to the baseline or standing with feet together with eyes closed, without foam.

4.2 Study 1: iPod Comparisons Baseline Results

SPSS version 17.0 was used to assess the descriptive statistical information for all participants for Study 1 and Study 2. For both Study 1 and Study 2, repeated measures general linear models were computed. Data from sixty-six subjects was included in the analysis of Study 1. Measures from nine participants were omitted due to recording errors, typically caused by movement of the measuring device (iPod) as subjects viewed the screen during the test prior to finishing the 10 second measure. Comparisons of the iPod results were calculated between (1) a stable surface, with conditions of feet together with eyes closed, single leg, single leg with eyes closed, tandem, and tandem with eyes closed, and (2) a foam surface, with conditions of feet together, feet together with eyes closed, single leg, single leg with eyes closed, tandem, and tandem with eyes closed. Data for the anterior/posterior (A/P) scores was compared separately from the medial/lateral (M/L) scores.

4.2.1 A/P Scores Comparing Trials, Leg Stance, and Foam Conditions

The questions posed for the anterior/posterior scores comparing trials, leg stance, and foam condition were as follows:

1. Is there a significant main effect between Trial 1, Trial 2, and Trial 3?

2. Is there a significant difference between single leg condition and tandem condition?

3. Is there a significant difference between the no foam condition and blue foam condition?

Significant main effects for these conditions are seen in Figure 4.1 and Figure 4.2.

FIGURE 4.1

SIGNIFICANT MAIN EFFECT A/P MEANS FOR STANCE CONDITION

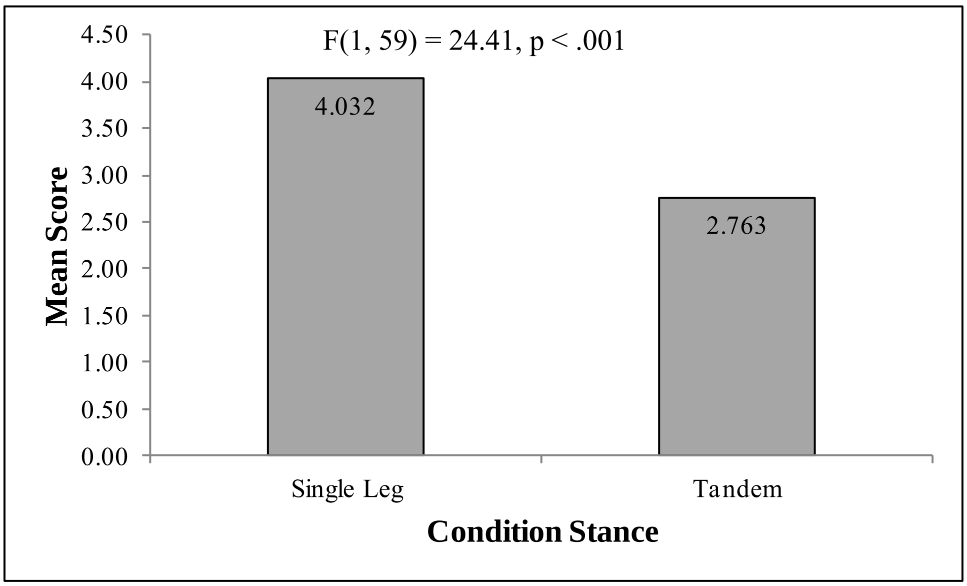
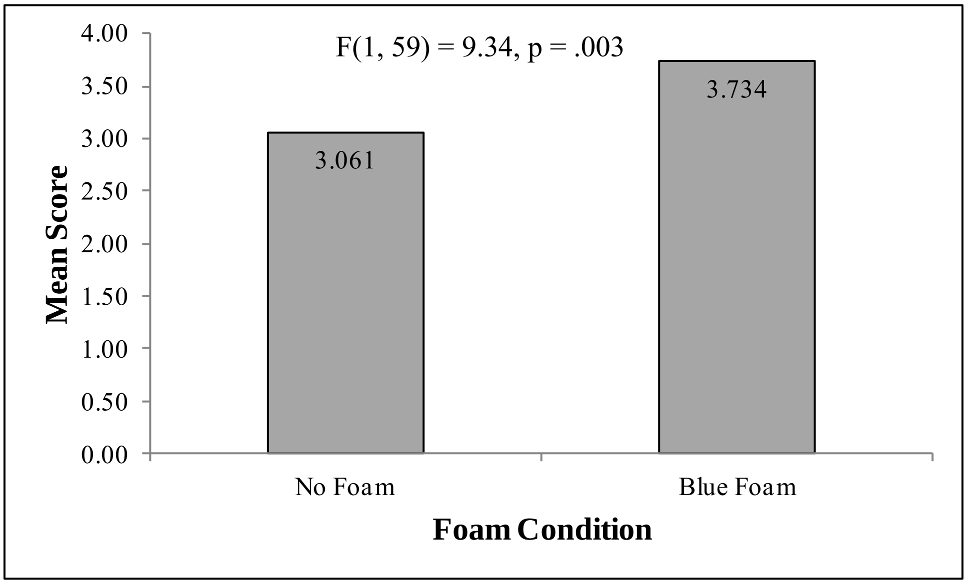


FIGURE 4.2

SIGNIFICANT MAIN EFFECT A/P MEANS FOR FOAM CONDITION



Statistical analysis was computed from sixty-six participants. A limiting factor for this analysis was the limited number of trials to compare, because these trials were all performed with eyes open. There was not a significant main effect between Trials 1, 2, or 3, and there were no interactions between trials and conditions. Results showed a significance main effect for the leg stance. Single leg A/P scores (M=4.032) were significantly higher than tandem A/P scores (M=2.763), $F(1,59) = 24.41$, $p < .001$, independent of trial and foam condition.

There was a significant main effect for the foam condition. The no foam condition A/P scores (M=3.061) were significantly lower than the blue foam A/P scores (M=3.734), $F(1,59) = 9.34$, $p = .003$

4.2.2 A/P Scores Comparing Trials and Leg Stance Conditions

The questions posed for the anterior/posterior scores comparing trials and leg stance conditions were as follows:

1. Is there a significant main effect between Trial 1, Trial 2, and Trial 3?
2. Is there a significant difference between double leg, single leg, and tandem conditions?

Significant main effects for these conditions are seen in Figure 4.3 and Figure 4.4.

FIGURE 4.3

SIGNIFICANT MAIN EFFECT A/P MEANS FOR TRIALS

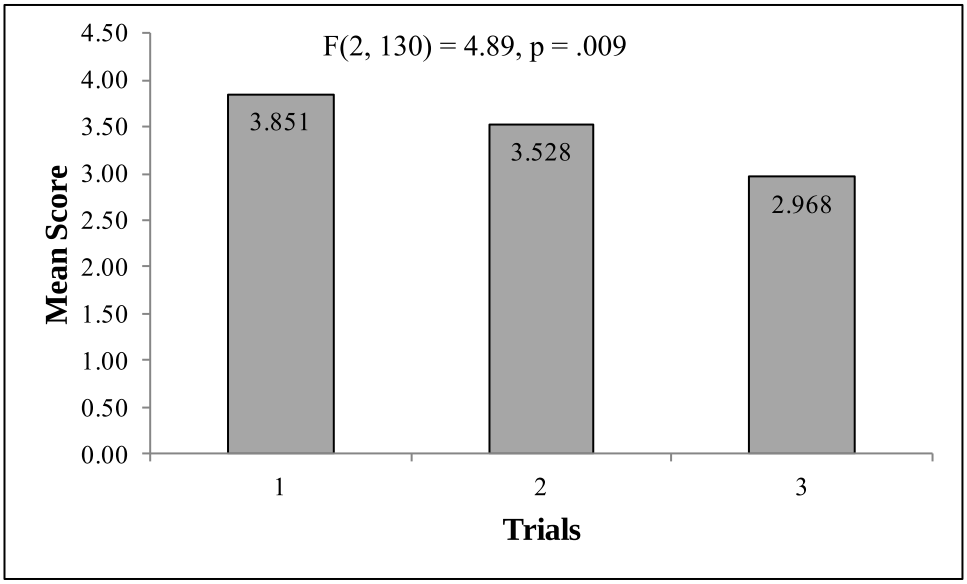
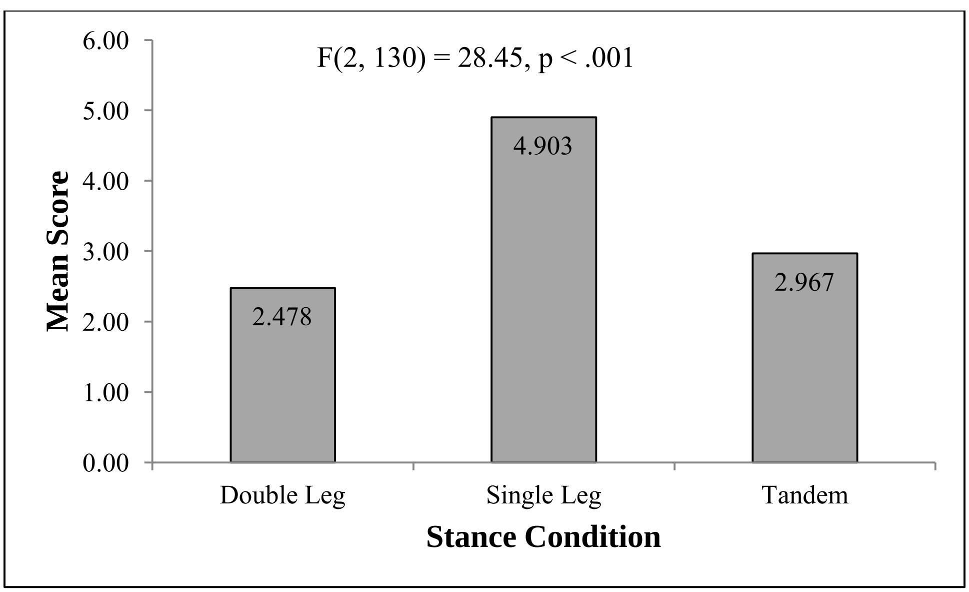


FIGURE 4.4

SIGNIFICANT MAIN EFFECT A/P MEANS FOR STANCE CONDITION



Statistical analysis was computed from sixty-six participants. Limiting factors for this analysis were all trials were completed with eyes closed, with the no foam condition, limiting trials to conditions to compare. There was a significant main effect for the trials. Trial 3's A/P scores (M=2.968) were significantly lower than both Trial 1's A/P scores (M=3.851) and Trial 2's A/P scores (M=3.528), $F(2, 130) = 4.89$, $p = .009$. The scores for Trials 1 and 2 were not significantly different. There were no interactions between the trials and conditions.

There was a significant main effect for the leg stance condition. The single leg A/P scores (M=4.903) were significantly higher than both double leg A/P scores (M=2.478) and tandem A/P scores (M=2.967), $F(2, 130) = 28.45$, $p < .001$. The scores for the double leg condition and the tandem condition were not significantly different.

4.2.3 M/L Scores Comparing Trials, Leg Stance, and Foam Conditions

The questions posed for the medial/lateral (M/L) scores comparing trials, leg stance, and foam condition were as follows:

1. Is there a significant main effect between Trial 1, Trial 2, and Trial 3?
2. Is there a significant difference between single leg condition and tandem condition?
3. Is there a significant difference between the no foam condition and blue foam condition?

Significant main effects for these conditions are seen in Figure 4.5 and Figure 4.6.

FIGURE 4.5

SIGNIFICANT MAIN EFFECT M/L MEANS FOR STANCE CONDITION

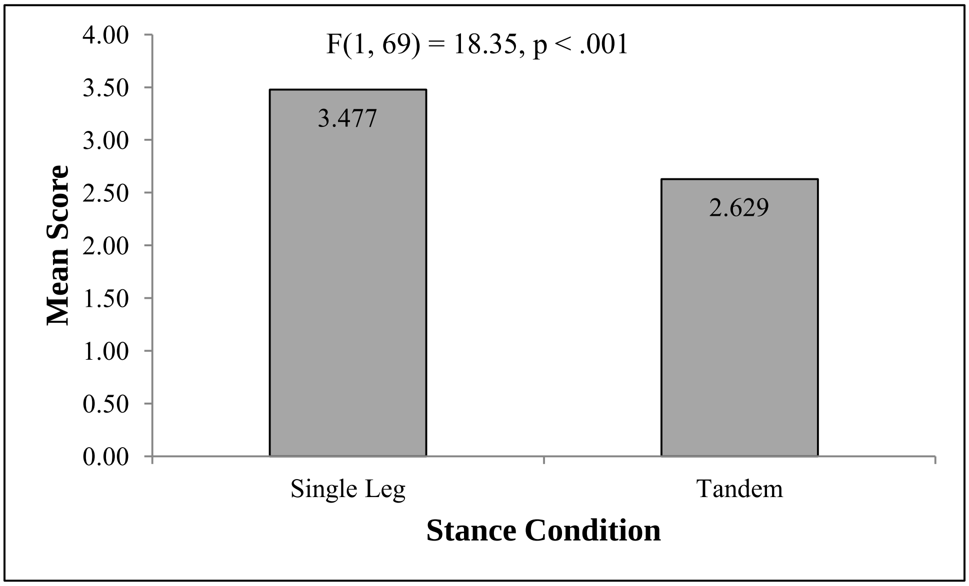
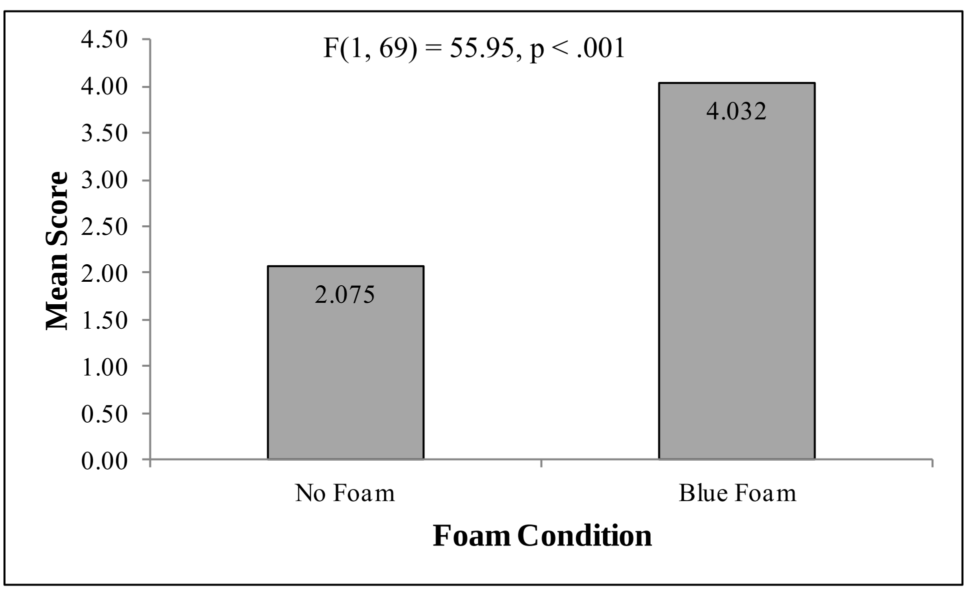


FIGURE 4.6

SIGNIFICANT MAIN EFFECT M/L MEANS FOR FOAM CONDITION



Statistical analysis was computed from sixty-six participants. A limiting factor for this analysis was the limited number of trials to compare. There was not a significant main effect between

Trials 1, 2, or 3, and there was not an interaction between trials or conditions. Results showed a significant main effect for the leg stance. Single leg M/L scores (M=3.477) were significantly higher than tandem M/L scores (M=2.629), $F(1, 69) = 18.35$, $p < .001$, independent of trial and foam condition.

There was a significant main effect for the foam condition. The no foam condition M/L scores (M=2.075) were significantly lower than the blue foam condition A/P scores (M=4.032), $F(1,69) = 55.95$, $p < .001$.

4.2.4 M/L Scores Comparing Trials and Leg Stance Conditions

The questions posed for the medial/lateral scores comparing trials and leg stance conditions were as follows:

1. Is there a significant main effect between Trial 1, Trial 2, and Trial 3?
2. Is there a significant difference between double leg, single leg, and tandem conditions?

The Significant interaction for this condition is seen in Figure 4.7 and Figure 4.8.

FIGURE 4.7

SIGNIFICANT INTERACTION M/L MEANS BETWEEN TRIALS DURING TANDEM CONDITION

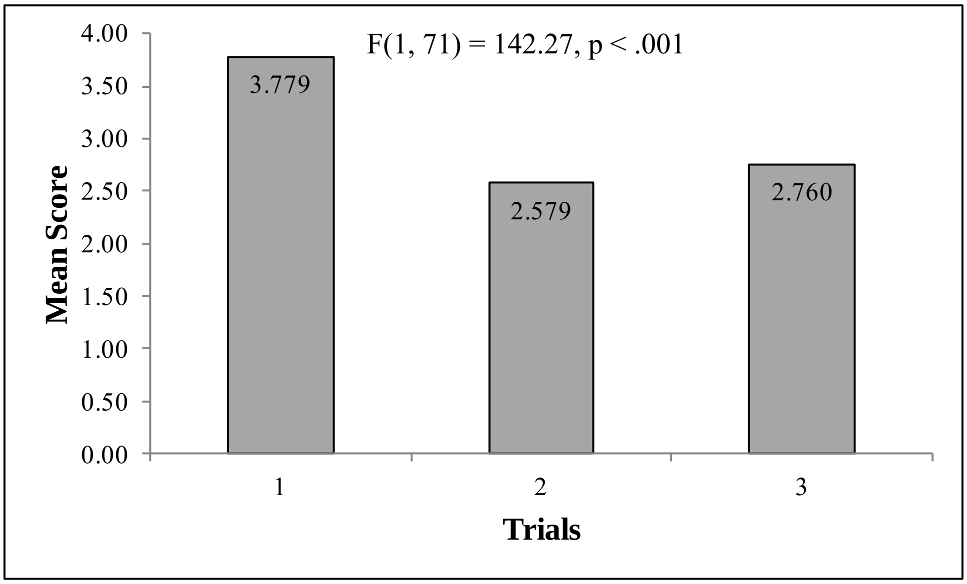
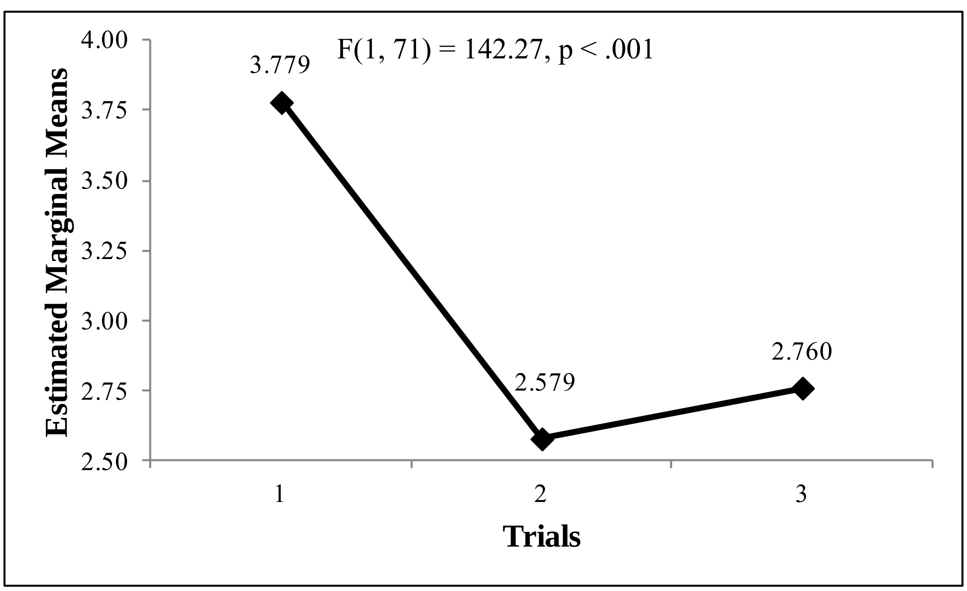


FIGURE 4.8

ESTIMATED MARGINAL M/L MEANS OF SIGNIFCANT INTERACTION OF TRIALS DURING TANDEM CONDITION



Statistical analysis was computed from sixty-six participants. There was a significant interaction between the trials and the leg stance condition. An interaction between Trials 1, 2, and 3 occurs, but only in the tandem condition. Trial 1's M/L scores (M=3.779) were significantly higher than both the Trial 2 M/L scores (M=2.579) and the Trial 3 M/L scores (M=2.760). Trial 2's M/L scores and Trial 3's M/L scores were not significantly different from each other.

4.3 Study 2: iPod versus BIODEX Comparisons Results

There were 57 participants that returned and completed Study 2. Balance values from both the iPod and the BIODEX Balance System SD were collected during the same assessment. Measures for Study 2 included (1) a stable surface, with conditions of feet together (baseline), feet together with eyes closed, single leg, and single leg with eyes closed, and (2) a foam surface with conditions of feet together, feet together with eyes closed, single leg, and single leg with eyes closed. All conditions were performed with eyes closed. The tandem condition was absent from this study, which limits the ability to compare data between Study 1 and Study 2.

4.3.1 A/P Scores Comparisons

The statistical analysis compared the A/P scores from the mobile device (iPod) and the BIODEX Balance System SD. The double leg and single leg conditions were compared, and the foam and no foam conditions were compared as well.

The Significant interactions for these conditions are seen in Figure 4.9 and Figure 4.10.

FIGURE 4.9

SIGNIFICANT INTERACTION A/P MEANS BETWEEN STANCE CONDITIONS WITH THE IPOD

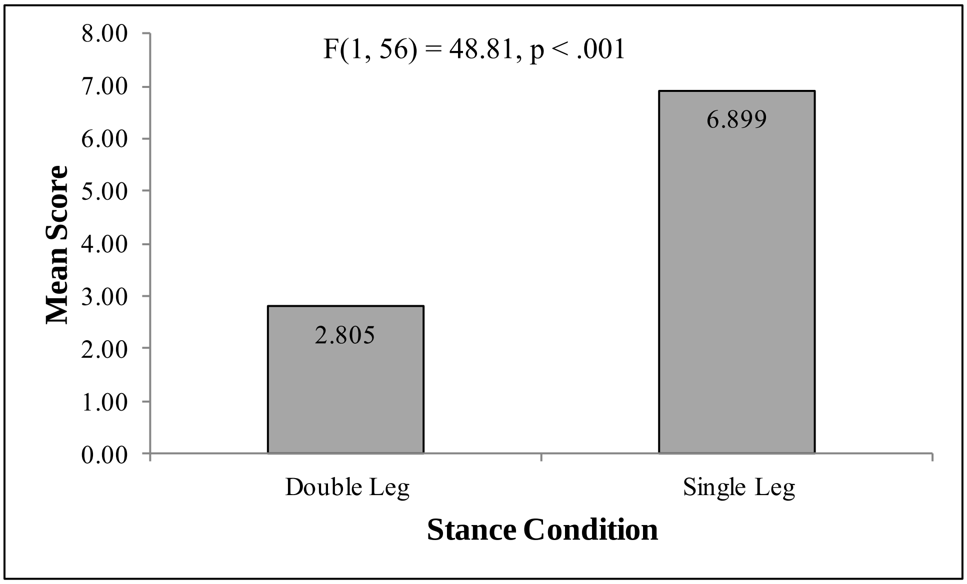
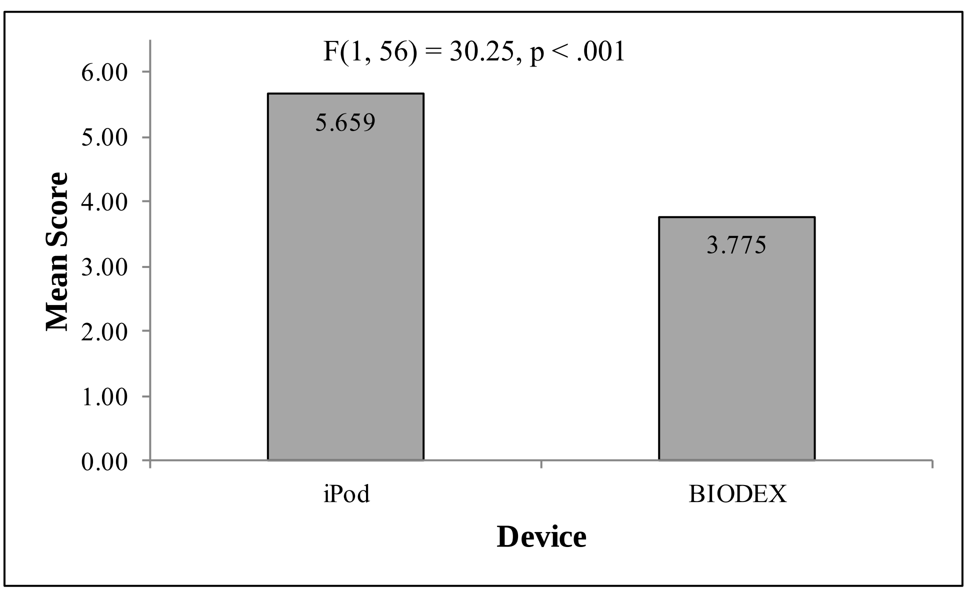


FIGURE 4.10

SIGNIFICANT INTERACTION A/P MEANS BETWEEN DEVICES IN THE FOAM CONDITION



There was a significant interaction between the devices and the stance conditions, $F(1, 56) = 48.81$, $p < .001$. The double leg A/P scores (M=2.805) were significantly lower than the single leg A/P scores (M = 6.899) only with the iPod device. There was no difference between the two leg scores measured by the BIODEX.

There was a significant interaction between the devices and the foam conditions, $F(1, 56) = 30.25$, $p < .001$. In the foam condition, the A/P scores measured by the iPod (M = 5.659) were significantly higher than the A/P scores measured by the BIODEX (M = 3.775). In the no foam condition, there was no difference between the two devices' A/P scores.

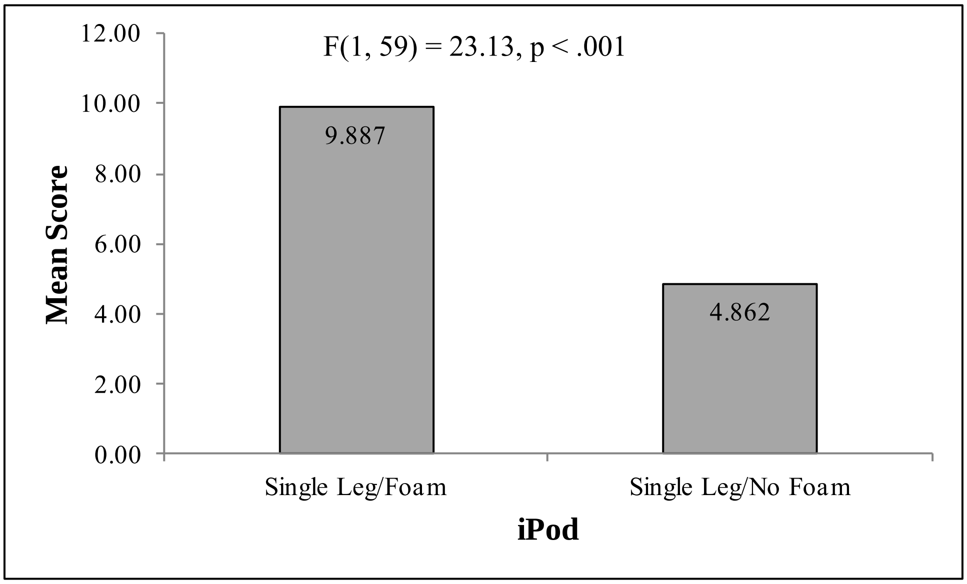
4.3.2 M/L Scores Comparisons

The statistical analysis compared the M/L scores from the mobile device (iPod) and the BIODEX Balance System SD. The double leg and single leg conditions were compared, and the foam and no foam conditions were compared as well.

The Significant interactions for these conditions are seen in Figure 4.11.

FIGURE 4.11

SIGNIFICANT THREE-WAY INTERACTION M/L MEANS BETWEEN THE STANCE AND FOAM CONDITIONS WITH THE IPOD



The three-way interaction (the devices x the stance conditions x the foam conditions) was significant, $F(1, 59) = 23.13$, $p < .001$. The single leg M/L scores in foam condition ($M = 9.887$) were significantly higher than the single leg M/L scores in the no foam condition ($M = 4.862$) with the iPod device only.

CHAPTER 5

DISCUSSION

5.1 Overview

This study was funded by Capacity Sports to compare the balance assessment measures from a mobile device application (iPod) utilizing accelerometric motion sensors against the balance assessment measures of a clinically valid and reliable balance platform (BIODEX Balance System SD) to determine if the application was a valid and reliable tool to assess postural balance. From the seventy-five participants, both Study 1 and Study 2 presented significant results. Study 1 found data to be in agreement with the hypothesis that the more unstable the assessment the higher the balance score compared to baseline or standing with feet together eyes closed without foam. Results from Study 2 showed a significant difference between standing with feet together compared to single leg stance and these values were not significantly different from the same measure in Study 1. Furthermore, without foam conditions with both instruments (iPod and BIODEX) recorded similar results. However, the BIODEX recorded significantly lower scores than the iPod when standing on foam. The iPod scores were similar to the same measure in Study 1, while the BIODEX standing on foam scores were similar to no foam.

5.1.1 Established Validity of the Study

Studies have shown that assessment of balance and implementing balance training programs can lead to prevention of injury, assess the neuromuscular effects of aging, decrease the risk of falling in the aging, provide rehabilitation, help diagnosis injury related to disease or trauma to the brain, determine neurological disorders, enhance functional or athletic performance, and provide an overall better understanding of the physiological systems contributing to postural movement and stability [1, 3, 10, 14, 17, 20, 25-30, 37, 46, 47, 76-87]. Though balance training programs and assessments are being utilized for many conditions and populations, proper assessment and measure of balance must be determined in order to select the appropriate method of balance training. For implementation of balance training programs to be successful, assessment protocols must be reliable, valid, and reproducible. Hundreds of studies have been published using accelerometric technology to determine human movement. Though the studies contribute to the field, studies that did not directly pertain to the current study were excluded. Those studies included accelerometric monitoring of energy expenditure, accelerometric monitoring of physical activity, and accelerometric monitoring of movement classifications. From the previous published studies, fifty-three studies were relevant to the current study. Of those studies, twenty-two evaluated conditions of balance during walking and gait mobility movements via accelerometry while ten studies using accelerometry assessed postural movement and stability in the aging and assessed the risk of falling in those with poor balance. Five studies assessed the effects of involuntary movements and the myotactic reflex in individuals with neuromuscular disease on stability using accelerometers. More specific to the current study, eight studies assessed postural balance during quiet standing with accelerometers, while four studies utilized smartphones with accelerometers to assess balance, postural sway, and gait in individuals. One study by Mayagoitia et al. (2002) utilized a triaxial accelerometer simultaneously with a force platform to assess ability to maintain balance while standing. In this study, the accelerometer was placed at the back of the subject at the height of the center of mass by means of a belt with the accelerometer attached, and data was collected from five performance parameters [88].

To the author's knowledge, the current study was the only study that utilized smartphone accelerometers to assess balance against the BIODEX Balance System SD, a clinically accepted balance assessment tool. Though studies have used mobile accelerometry, there have not been any studies that have validated mobile smartphone accelerometers against a clinically validated balance tool until the current study.

5.1.2 Objectives of the Study

The Objective of Study 1 was to assess balance in the most stable position and categorize the score as baseline. Once baseline was established, the assessments that followed were in a less stable position, ending with standing on one foot on a foam pad. The objectives were to continually make subjects less stable and identify whether the software application was able to present data consistent with the increasing instability and if the measureable change was consistent with the graded difficulty of the balance test. For each measure, as the balance task became progressively more difficult, the mobile device recorded an increase in the balance score. Additionally, because each balance task was performed three times, reproducibility comparisons could be made. These results demonstrated that trial 1 scores were significantly higher than trial 2 and trial 3, with no difference between trials 2 and 3, suggesting that a familiarization test may be necessary for consistent scores.

The objective of Study 2 was to compare the measurements of the software application with the results from the BIODEX Balance System SD through each of the four conditions of the stable and unstable measurements.

5.2 Comparison of Trends between Devices

As discussed in Chapter 2, previous published literature has shown that increasing the difficulty of stability conditions will present a decrease is postural balance in individuals. The data collected by the iPod is a good representation of this expected outcome. Figure 5.1 and Figure 5.2 show the trend in scores of increasingly difficult conditions from Study 1.

FIGURE 5.1

CHANGE IN A/P SCORES WITH CHANGE IN STABILITY CONDITION (IPOD)

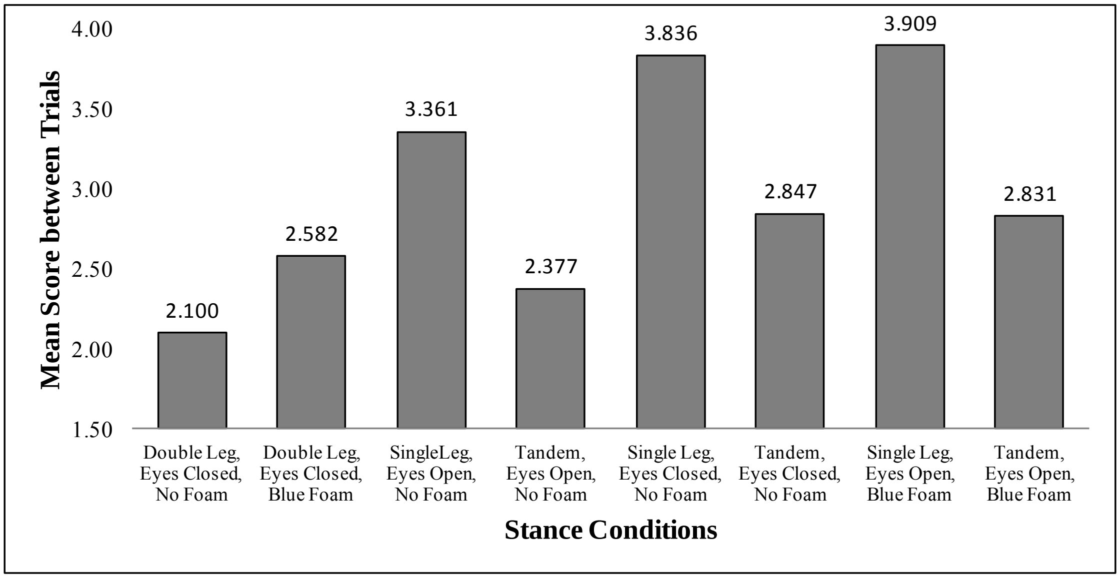
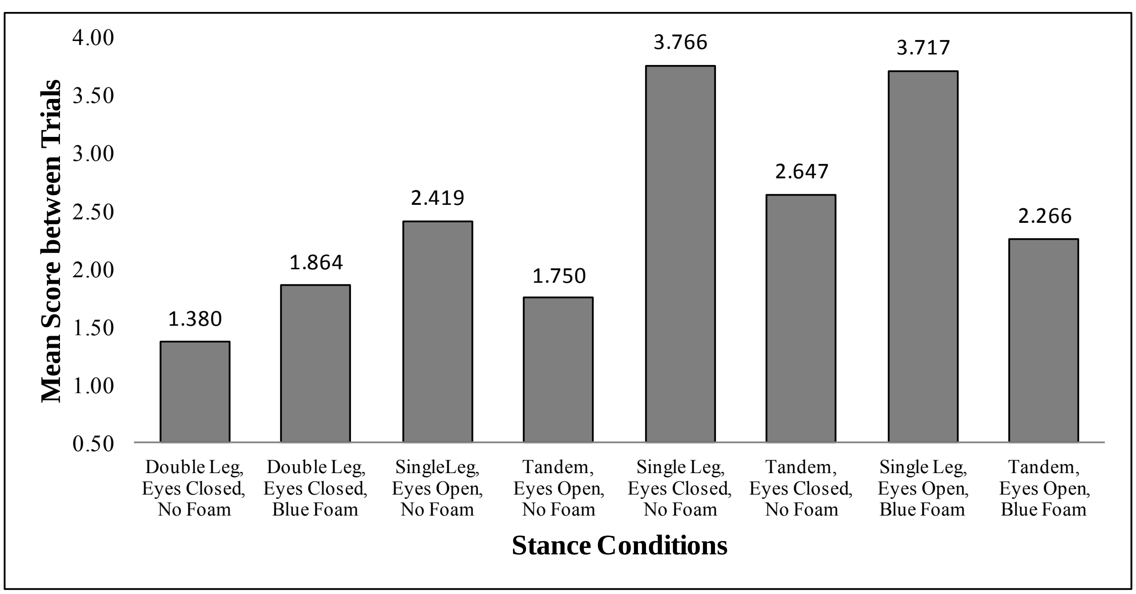


FIGURE 5.2

CHANGE IN M/L SCORES WITH CHANGE IN STABILITY CONDITION (IPOD)



These figures represent a linear trend in changes in condition. As the conditions increase in difficulty, the average scores increase, meaning the participants' balance decreased. The trend with the tandem condition is obviously different from the norm, suggesting a familiarization with this condition is needed.

The trend in scores is also seen within the iPod between two different studies. Figure 5.3 and Figure 5.4 represent the change in scores with change in conditions between studies.

FIGURE 5.3

CHANGE IN A/P SCORES WITH CHANGE IN CONDITION BETWEEN STUDIES (IPOD)

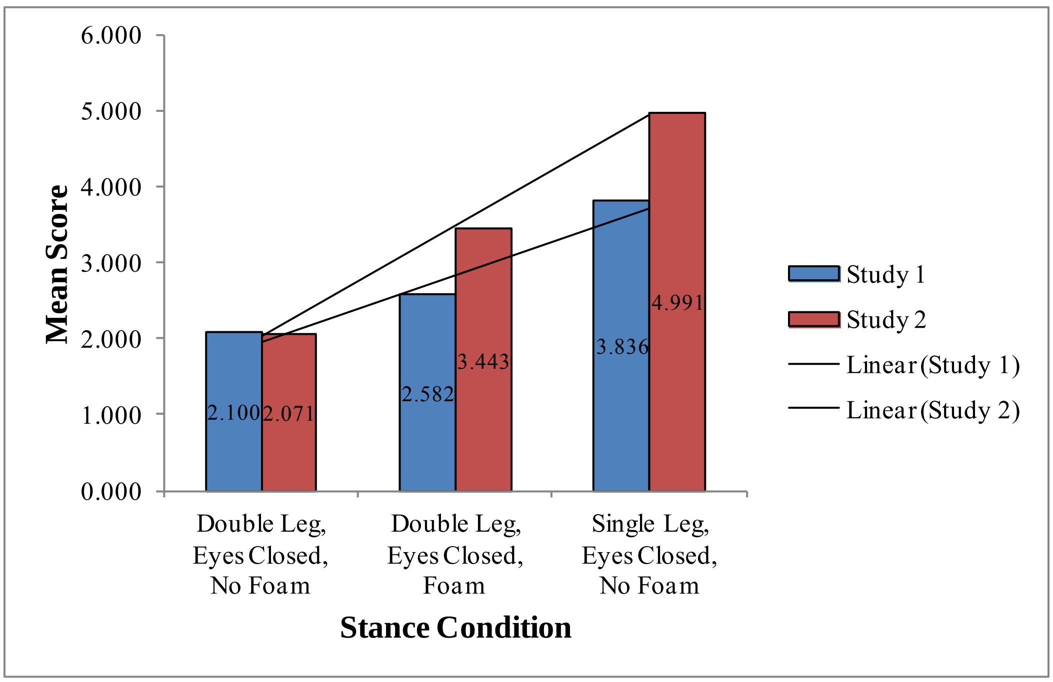
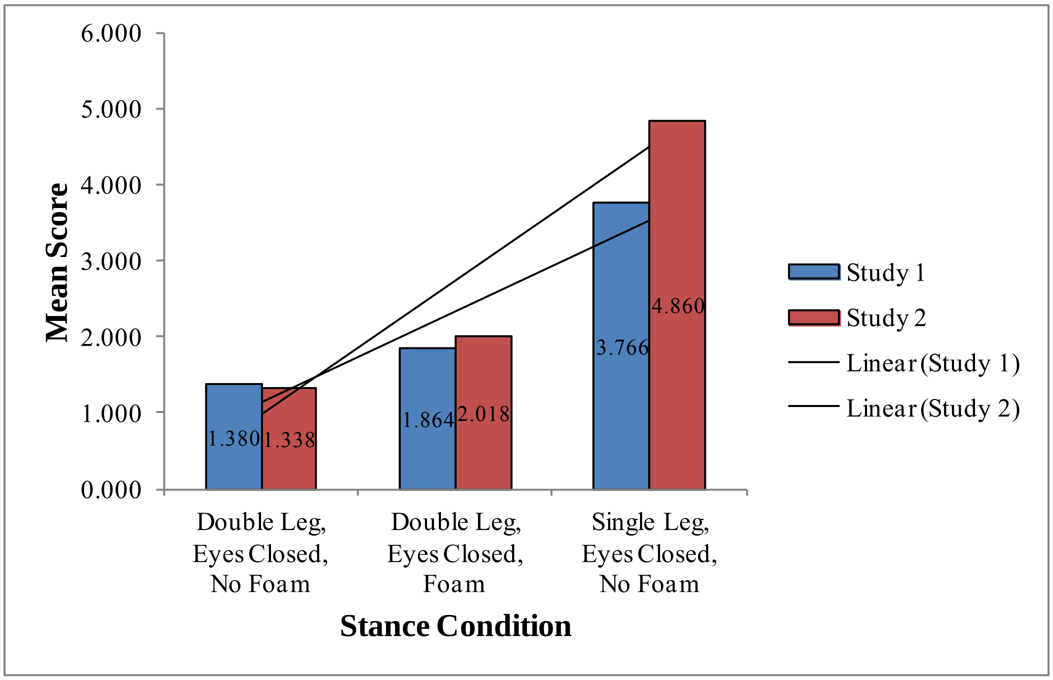


FIGURE 5.4

CHANGE IN M/L SCORES WITH CHANGE IN CONDITION BETWEEN STUDIES (IPOD)



These figures represent a linear trend in changes in condition, similar to Figures 5.1 and 5.2. As the conditions increase in difficulty, the average scores increase, meaning the participants' balance decreased. This also shows reproducibility, because similar trends are seen on different days during different studies but with the same iPod application.

The trend in scores between the iPod and the BIODEX can also be observed. Figure 5.5 and Figure 5.6 represents this trend.

FIGURE 5.5

MEAN A/P SCORE FOR CONDITIONS BETWEEN IPOD AND BIODEX

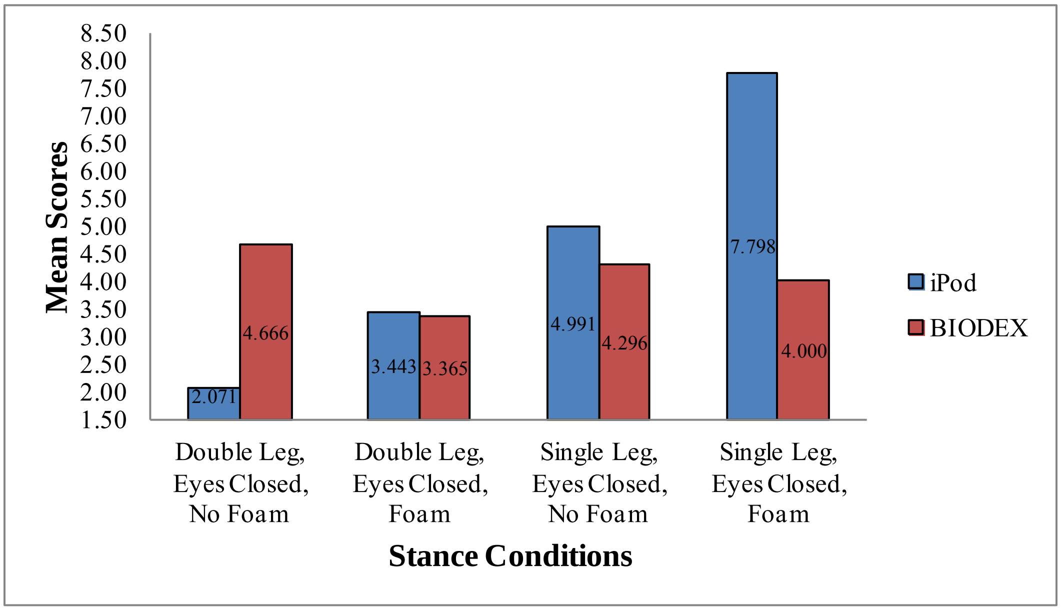
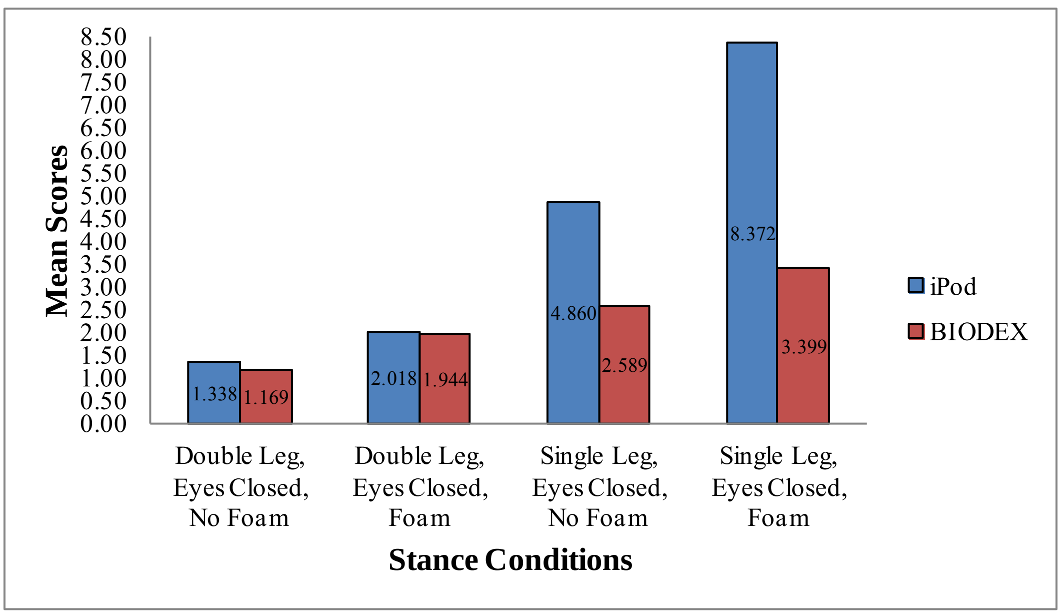


FIGURE 5.6

MEAN M/L SCORE FOR CONDITIONS BETWEEN IPOD AND BIODEX



These score scores represent the trends between the iPod and the BIODEX. In both Figures 5.5 and 5.6, a similar trend occurs with the iPod as conditions become more difficult. Trends are similar between the BIODEX and iPod in Figure 5.6, but do not represent the same with the A/P scores in Figure 5.5. In figure 5.5, the single leg, eyes closed, on foam condition would expect high scores due to the instability factor of the condition. The iPod represents the change, but the BIODEX does not. This indicates that the BIODEX and the IPod are interpreting different movements. This was statistically represented in Chapter 4.

5.3 Comparison of Stability Index

The current study utilized the BIODEX Balance System SD, which uses a circular platform that is free to move about the anterior-posterior (AP) and medial-lateral (ML) axes simultaneously and measures the degree of tilt about each axis during dynamic conditions, providing more specific information on the ankle joint mechanoreceptors that offer proprioceptive feedback necessary for balance control [2, 18, 22]. As discussed previously in Chapter 2, the BBS calculates the medial-lateral stability index (MLSI), the anterior-posterior stability index (APSI), and the overall stability index (OSI) by means of strain gauges, which measure the change in pressure and force within the springs of the underside of the platform [59, 60]. The units that represent the stability index are interpretations of the change in strain, calculated by undisclosed calculations from BIODEX Medical Systems, Inc. The OSI represents the variance of foot platform displacement in degrees from level, in all motions during a test. A high Stability Index is indicative of a subject having difficulty maintaining a level platform position and may represent poor neuromuscular control [22]. Zero (0) represents a starting point for a perfectly balanced state or, center of balance, and the displacement for each variance is subtracted from zero [22]. The variance "Y" corresponds to the Anterior/Posterior Stability Index (APSI), and represents the variance of foot platform displacement in degrees, from level, for motion in the sagittal plane [22]. A high APSI score in this direction may indicate poor neuromuscular control of (1) the Quadriceps and/or Hamstring muscles and (2) the Anterior/Posterior compartment muscles of the lower leg [22]. The variance "X" corresponds to the Medial/Lateral Stability Index (MLSI), and represents the variance of foot platform displacement in degrees, from level, for motion in the frontal plane [22]. A high MLSI score in this direction may be indicative of poor neuromuscular control of the inversion or eversion muscles of the lower leg, both bilaterally and unilaterally [22]. The MLSI and the APSI assess the fluctuations from horizontal along the AP and ML axes of the BBS, respectively, while in contrast, the OSI is a composite of the MLSI and APSI, and is sensitive to changes in both directions [18]. Similarly, the Concussion Manager Smartphone Application measures a position movement, or variance from the center point. Unlike the BIODEX however, the application measures G-forces. These movements are calculations of jerk- the change of accelerations- instead of accelerations themselves [24]. The magnitude of jerk describes the changes of body accelerations, independently from the sensor orientation or any estimates for gravitational acceleration [24]. Given two consecutive accelerations, the difference vector can be calculated, which corresponds to the average jerk in time interval [24]. Assuming that the orientation has not changed in this time interval, the gravitational component is the same in both time steps, and they are cancelled out, giving the difference of body accelerations without knowing gravitational acceleration [24]. In addition, the magnitude of difference vector is orientation-independent, and thus accurate [24]. These calculations provide the sway index, and though are different units then what the BBS provide, can be compared with the sway indexes of the BBS. The application measures a change from the first position to all subsequent positions during the test. For example, if X_1 represents a starting point for a perfectly balanced state or, center of balance, and X_2 represents a change in position, then X_1 is subtracted from X_2 to determine the displacement from center. X_1 is subtracted again from the following position change, and is represented as X_3-X_1, and so on.

5.4 Limitations with the Technology

Six major limitations were evident from conducting this study. The first limitation was the difference in place of measurement between the mobile device and the BIODEX Balance System SD. The mobile device measures the stability index from center of mass (sternum level of the chest), where the device is held during the test while the BBS measures stability index from the degree of tilt within the ankle from the base of the platform. The results from Study 2 showed a significant difference between standing with feet together compared to single leg stance, and these values were not significantly different from the same measure in Study 1. However, when standing on foam the BBS recorded significantly lower scores than the mobile device. The mobile device scores were similar to the same measure in Study 1, while the BBS standing on foam scores were similar to no foam. This may be a result of consistency of the BBS Foam Pad being used with subjects that have above average balance and have a high level of stability of the foot and ankle. The foam may have absorbed the movements for these participants, resulting in similar balance scores with the without foam condition. This may suggest an advantage of measuring human balance at or above the center of gravity with a device such as the iPod, because it is practical and consistent with current balance assessments tests, such as the One-leg Balance Test and the Balance Error Scoring System (BESS). However, the difference between the measurement from the center of mass and the movement of the ankle may provide inconsistent results. Another limitation was the difference in measurement units. As discussed in the previous section, the BBS provides units of sway index from changes in strain from the springs of platform, while the application provides units of sway index from G-forces and changes in accelerations. Though the application is more applicable to current balance measures being used, it is difficult to validate against the BBS due to different units of measure. Another limitation is the error of the participant while using the device. If the participant moves or looks at the screen of the iPod before the test has ended, the movement of the device can affect the data. Furthermore, if the participant makes an error on the first position (center of balance), then all the subsequent positions will be effected because the test did not start at a perfectly balanced state. A forth limitation was the participant's technique. Many of the participants had to be corrected during the trials because they failed to adhere to the protocol of the test. The device is to be placed on the chest, while holding it with both hands. Many participants held the device with both hands, but held it one to two inches off of the chest. The results may be inconsistent or inaccurate because the device is recording movements of the hands and arms, rather than the movements of the center of mass. A fifth limitation is the need for familiarization with conditions, specifically, the tandem stance condition. Many participants had never stood in a tandem stance, and it was evident during testing because many continued to shift their weight distribution back and forth between legs, ultimately performing single leg stance. This is represented by the data. A final limitation was the equation used for the application at the time of testing. The equation, as discussed in the previous section, measures G-forces; it measures a change in acceleration from the first position to all subsequent positions during the test. While this is useful for determining changes for groups, it does not account for each participant's individual movements. This is represented by Figure 5.7 and Figure 5.8.

FIGURE 5.7

DIFFERENCE IN A/P SCORE FROM DOUBLE LEG TO SINGLE LEG CONDITION

BETWEEN THE IPOD AND BIODEX

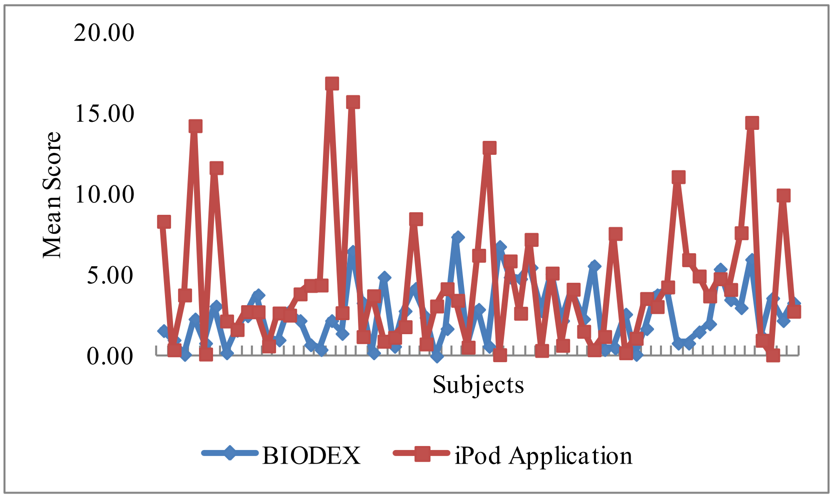


FIGURE 5.8

DIFFERENCE IN A/P SCORE FROM DOUBLE LEG TO SINGLE LEG CONDITION

BETWEEN THE IPOD AND BIODEX WITH OUTLIERS REMOVED

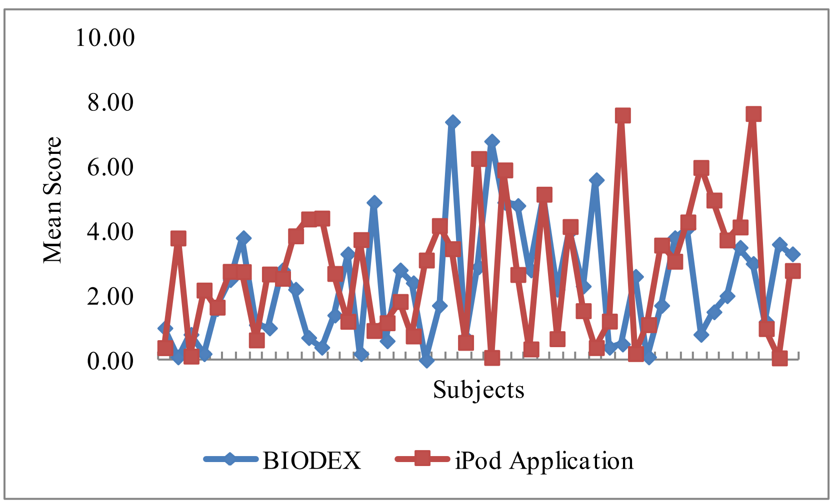


Figure 5.7 represents the trends in scores between the iPod and BBS. Though it is indicative that trends in data are similar, the outliers from the iPod data are included in calculating mean scores, representing very high scores. Figure 5.8 represents the data with removal of the outliers. It

shows more clearly the trends scores between the iPod and BBS. The new equation for the application measures a change in acceleration from position to position during the test, providing more accurate measurements for individuals.

5.5 Conclusions

This study compared the balance assessment measures from a mobile device application (iPod) utilizing accelerometric motion sensors against the balance assessment measures of a clinically valid and reliable balance platform (BIODEX Balance System SD). This study supported published findings that accelerometry is valid for measuring human balance because the balance scores measured by the accelerometers within an iPod appear to be a valid and consistent method of measurement when compared to the BIODEX. Results from this study are promising and show consistency in the values recorded. Additionally, feedback on usability of the Smartphone software was positive, with participants agreeing that the instruction on how to perform the balance test as well as the ability to use the device was easy to follow.

5.6 Recommendations for Further Research

This study raised further questions on the effectiveness of reliably assessing the balance of different populations. Further studies should investigate the reliability and validity of balance assessment in multiple populations, such as the aging, diseased, adolescents, and adults. Other further studies should investigate reliability and validity of balance assessment in athletes, specifically those in contact sports where injury to the head and brain are more likely to occur, such as football, soccer, and basketball. Finally, baseline studies with individuals who have suffered a brain or head injury, like a concussion, may provide comparative information between individuals who have suffered an injury that affected balance and those who have not.

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