The Effect of Foot Type on Star-Excursion and Time-to-Boundary Measures During Single-leg Stance Balance Tasks.

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**ABSTRACT**

ROBERT JEFFREY BONSER: The effect of foot type on star-excursion and time-to-boundary measures during single-leg stance balance tasks.
(Under the direction of Steve Zinder, PhD, ATC)

**Objective:** To determine if single-leg balance performance differs among individuals of different foot types using time-to-boundary (TTB) and Star Excursion Balance tests (SEBT). And to determine if there is a relationship between Foot Posture Index-6 (FPI-6) scores, TTB mean minima and SEBT scores. **Subjects:** 61 total subjects; 20 supinated, 21 neutral, 20 pronated. **Measurements and Data:** FPI-6 was used to classify foot type. TTB measurements in the medial/lateral and anterior/posterior direction were evaluated. SEBT maximum reach scores in the anterior, posteromedial, and posterolateral directions were also evaluated. Nine separate one-way ANOVAs, and a correlation matrix were used for statistical analysis. **Results:** A significant difference was found between pronated and neutral foot type for TTB mean minima in the medial/lateral direction. No significant differences were found between foot type for any other dependent variable. No significant relationships were discovered between FPI-6, SEBT, and TTB scores. **Discussion:** Pronated feet demonstrated better balance performance than neutral feet in the frontal plane, possibly due to a wider base of support. The SEBT and TTB scores have no relationship, thus measuring different aspects of balance performance.

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# CHAPTER I

# INTRODUCTION

## An Overview

During athletic and recreational events, the ankle is the most commonly injured joint in the body because of the large mass it supports and the large amount of ground reaction force it transfers relative to its small size (Brand, Black et al. 1977; Morrison and Kaminski 2007). In 1984, Soboroff et al (Soboroff, Pappius et al. 1984) estimated that the costs associated with the treatment of ankle injuries in the United States exceeded two-billion dollars a year. One may estimate that since 1984, this cost has significantly increased due to inflation alone. To prevent and treat injuries, techniques such as taping and bracing are commonly used in the clinical setting. Taping and bracing have been demonstrated to be effective in the prevention of ankle sprains (Sitler, Ryan et al. 1994; Sharpe, Knapik et al. 1997). However, treatments of this type are costly. Olmsted et al. (2004) estimated the seasonal cost of taping 26 athletes with a history of sprain would be $2778, and bracing would be $910 per season. Clearly, it is beneficial for athletic training programs to find the most cost-effective way to help prevent ankle sprains.

Ankle injuries may be prevented more effectively by gaining insight into risk factors for injury. Poor balance performance is one factor that has been identified in a prospective study (Beynnon, Renstrom et al. 2001). Balance performance is the ability of the body to maintain the center of gravity within the body's base of support using a combination of vestibular, visual and proprioceptive feedback (Guskiewicz and Perrin 1996). Several studies have determined that compromised balance performance is associated with increased risk for ankle injury (Tropp, Ekstrand et al. 1984; Watson 1999; McGuine, Greene et al. 2000; Beynnon, Renstrom et al. 2001).

Individuals with abnormal foot types may be at risk for ankle injury because foot type has been theorized to influence normal foot mechanics. (Hertel, Gay et al. 2002; Olmsted 2004; Cote, Brunet et al. 2005; Tsai, Yu et al. 2006). There are three categories of intrinsic foot types; pronated, neutral, and supinated (Dahle, Mueller et al. 1991). It has been theorized that only 15-17% of the population has a "normal" foot type, with neutral alignment (McPoil, Knecht et al. 1988; Smith-Oricchio and Harris 1990). Pronated foot types are characterized by a flat medial longitudinal arch, calcaneal eversion and forefoot varus, whereas supinated foot types are classified as having a rigid high medial longitudinal arch with calcaneal inversion and forefoot valgus. The two basic functions of the foot are to adapt to ground surface while facilitating shock absorption, and to function as a rigid lever to propel the body in space (Tiberio 1988). A neutral foot type is at a mechanical advantage to perform these functions (Tiberio 1988). On the other hand, a pronated foot type is generally more loose-packed, causing the midtarsal joint to unlock during ambulation which allows the foot to act as a shock absorber, but may decrease the ability to act as a rigid lever (Tiberio 1988). The supinated foot is more rigid, which causes the foot to act more efficiently as a rigid lever for propulsion, but not as efficiently as a shock absorber (Levinger, Murley et al. ; Tiberio 1988; Rome and Brown 2004).

While it has been theorized that foot type is linked to balance performance, results from previous studies remain inconclusive. While comparing center of pressure (COP) measures during a single-leg balance across foot types Hertel et al. (2002) demonstrated that the pes cavus (supinated) foot exhibited greater center of pressure velocity and center of pressure area than the pes planus (pronated) foot, indicating the supinated foot is associated with poor balance performance. Contrary to Hertel et al., another study (Olmsted 2004) that assessed the effect of foot type on static and dynamic postural control before and after orthotic intervention found no significant difference in postural control between individuals with varying foot types, yet observed a significant improvement in postural control after orthotic intervention for the pes cavus foot compared with neutral and pes planus feet. In a slightly different study, Cote et al. (2005) observed the effect of pronated and supinated foot types on static and dynamic postural stability (Star-excursion test). While the investigators observed no significant difference between foot type in a static posture, they demonstrated that individuals with supinated foot type exhibited better dynamic balance during the star-excursion task in several directions. These findings suggested that supinated foot may be better at adapting functionally to ground surfaces (Cote, Brunet et al. 2005). Contrary to the findings reported by Cote et al., in the most recent study examining the effects of foot type on balance performance, Tsai et al. (2006) observed that individuals with a supinated foot type have poorer balance in the medial/lateral direction than those with a pronated foot type. Inconsistencies in the findings from these studies indicate that no firm conclusion has been reached as to which foot type, if any, may exhibit poorer balance performance in individuals.

The inconsistent finding of previous studies regarding the effects of foot type on balance performance may be attributed, in part, to inaccuracy of the methods used to classify foot types. In studies by Hertel et al. (2002) and Olmsted et al. (2004) the foot type was assessed in a non-weight bearing position, while the task was performed in a weight bearing position. Additionally, the visual assessment and measurement used in these studies has been shown to have poor to moderate intratester and intertester reliability (ICC .32 - .79), indicating the need for a better foot classification tool (Elveru, Rothstein et al. 1988; Picciano, Rowlands et al. 1993; Cowan, Robinson et al. 1994; Somers, Hanson et al. 1997; Razeghi and Batt 2002). Alternatively a study by Cote et al. (2005) used a navicular drop test, which classifies foot types in a weight bearing position. Though the navicular drop test may be a more valid assessment of foot type than a non-weight bearing assessment, poor intertester and intratester reliability ICC limit its ability to accurately classify foot types (0.33 - 0.79) (Picciano, Rowlands et al. 1993; Vinicombe, Raspovic et al. 2001; Razeghi and Batt 2002; Redmond, Crosbie et al. 2006). Lastly, the study by Tsai et al. (2006) assessed foot type using the weight bearing measures outlined by Jonson and Gross (Jonson and Gross 1997). Though these measures had a high intertester and intratester reliability (ICC .65-.97), they have not been validated against any other measure of foot type (Razeghi and Batt 2002). Thus, there remains a need to find a valid and reliable measure to classify foot type in order to assess differences between the foot types in balance performance.

A novel validated and reliable foot scoring system called the Foot Posture Index 6 (FPI-6) **(Appendix 1)** developed by Redmond et al. (Redmond, Crosbie et al. 2006), has been increasingly used to classify foot type since being published in 2006 (Burns, Keenan et al. 2005; Redmond, Crosbie et al. 2006; Cain, Nicholson et al. 2007; Cornwall, McPoil et al. 2008; Redmond, Crane et al. 2008). The FPI-6 assessment involves visual inspection of six landmarks on the foot in a weight bearing posture (Redmond, Crosbie et al. 2006; Redmond, Crane et al. 2008). Based on the grading of the six criteria, the subjects are classified into five foot types: highly pronated, pronated, neutral, supinated, highly supinated. In recent studies, lower FPI-6 scores (supinated foot type) have been linked to overuse injuries in indoor soccer players and triathletes. (Cain, Nicholson et al. 2007). Another study demonstrated that pronated foot posture was associated with chronic plantar heel pain (Irving, Cook et al. 2007).

In addition to foot type assessment, the inconsistent findings in previous literature regarding the effects of foot type on balance performance may also be attributed to low sensitivity of balance performance measures. Balance performance is often assessed based on the movement of the center of pressure (COP) during a balance trial (Guskiewicz and Perrin 1996; Palmieri, Ingersoll et al. 2002). Traditionally, maximum excursions, peak velocity, and total sway area have been calculated as a measure of balance. However, interpretation of traditional center of pressure measures is not fully understood, making it difficult to draw clinical relevance from findings. While some investigators consider higher COP excursions (both magnitude and velocity) to be associated with poor balance (Tropp, Ekstrand et al. 1984; Guskiewicz and Perrin 1996; Watson 1999; McGuine, Greene et al. 2000) others suggest that variability is a natural human response and will allow for greater adaptation to ground reaction forces (Newell, REA et al. 1993; Beynnon, Renstrom et al. 2001; Ross and Guskiewicz 2004; Brown and Mynark 2007). In addition, the traditional COP measures may not accurately represent balance because variables such as maximum excursions and peak velocity can be influenced by a single point in the data set, and thus may not represent the overall balance performance.

A novel way of analyzing balance performance called time-to-boundary (TTB) was developed by Hertel et al. (2006). TTB uses standard COP measurements in a way that incorporates both spatial (displacement) and temporal (velocity and acceleration) aspects of postural sway, and is thought to be a more sensitive assessment of balance performance than traditional COP variables (Haddad, Gagnon et al. 2006; Hertel, Olmsted-Kramer et al. 2006; Hertel and Olmsted-Kramer 2007). TTB is an estimation of the time it would take for the COP of any given subject to reach the edge of the base of support if the COP were to continue on its trajectory at instantaneous velocity (Hertel, Olmsted-Kramer et al. 2006). A low TTB minima indicates greater postural instability because it indicates that the subject will have less time to execute a postural correction due to the COP being close to going outside of the edge of the base of support (McKeon and Hertel 2007). A recent study examined the effects of chronic ankle instability (CAI) compared to healthy individuals on TTB measures and found that the CAI group has significantly lower TTB measures (Hertel and Olmsted-Kramer 2007). Contrarily, two studies found no significant differences in balance performance between those with chronic ankle instability and healthy individuals using traditional measures of center of pressure (Isakov and Mizrahi 1997; Baier and Hopf 1998), indicating that the TTB may be a more sensitive analysis of balance performance.

Lastly, the Star Excursion Balance Test (SEBT) is a dynamic reach test, used as a functional assessment of balance performance. The SEBT has been shown to be sensitive enough to detect deficits between subjects and predict future potential injury risk (Munro and Herrington). In a study by Plisky et al. (2006), there was a correlation between decreased SEBT performance and lower extremity injury in high school athletes. Additionally, the SEBT has been used to detect differences in balance performance between those with and without chronic ankle instability (Olmsted, Carcia et al. 2002).

**Purpose and Clinical Relevance**

The relationship between foot type and balance performance needs to be conducted using a reliable and validated foot type assessment tool and sensitive balance performance measures. Therefore, the purpose of this study is two-fold. The primary purpose of this study is to determine if single-leg balance performance differs among individuals of different foot types using time-to-boundary and Star Excursion Balance tests. The secondary purpose is to determine if there is a relationship between FPI-6 scores, TTB mean minima and SEBT scores. Establishing a relationship may not only give insight into which foot type may be more at risk for ankle injury, but also help us to determine if the FPI-6 is a good predictor of balance performance measures, allowing us to predict balance performance based on clinical assessment of foot type. This would help us to identify and treat athletes who may be in greater need of prophylactic intervention, thus preventing more ankle injuries and reducing the financial expenses for athletic training programs.

We expect to see lower TTB minima values in supinated foot type compared to the pronated and neutral foot type. Also, we expect to see a positive correlation between FPI-6 scores and TTB measures. This means that we expect those with more supinated feet (lower FPI-6 scores) to exhibit poor balance performance (lower TTB minima), and those with pronated feet (higher FPI-6 cumulative scores) to exhibit improved balance performance (higher TTB minima). We also expect to see a greater maximum reach in those with pronated feet than those with supinated or neutral.

## Research Questions

1) Is there an effect of foot type on time-to-boundary measures during a static single-leg stance task?
2) Are maximum reach distances different between foot type during the Star-Excursion Balance Test?
3) Is there a relationship between FPI-6 scores and TTB minima during bare-foot single leg stance?
4) Is there a relationship between FPI-6 scores and SEBT max reach during bare-foot balance tasks?
5) Is there a relationship between TTB measures and SEBT max reach during bare-foot balance tasks?

## Independent Variables

1) Foot Type as assessed using FPI-6
   a) Pronated foot type
   b) Normal foot type
   c) Supinated foot type

## Dependent Variables

1) TTB absolute minima (ML)
2) TTB mean minima (ML)

3) TTB standard deviation of minima(ML)

4) TTB absolute minima (AP)

5) TTB mean minima (AP)

6) TTB standard deviation of minima (AP)

7) Star Excursion Mean Maximum Reach (Anterior, Posteromedial, Posterolateral)

**Null Hypothesis**

1) $H_0$ = There is no significant difference in TTB absolute minima between supinated, pronated and neutral feet during bare-foot single leg stance.

   a) $H_{0\,=}$ $TTBmin_{neutral}$=$TTBmin_{supinated}$ = $TTBmin_{pronated}$

2) $H_0$ = There is no significant difference in mean maximum reach distance between foot type during bare-foot single leg stance.

   a) $H_{0\,=}$ $SEBTmax_{pronated\,=}$ $SEBTmax_{supinated\,=}$ $SEBTmax_{neutral}$

3) There is no relationship between cumulative FPI-6 scores and TTB mean minima.

   a) $H_{0\,=}$ TTBavg = FPIscores

4) There is no relationship between cumulative FPI-6 scores and SEBT max reach scores.

   a) $H_{0\,=}$ SEBTavg = FPIscores

5) There is no relationship between TTB mean minima and SEBT max reach scores.

   a) $H_{0\,=}$ TTBavg = SEBTavg

**Research Hypothesis**:

1) $H_1$ = Supinated feet will exhibit lower TTB minima than both pronated and neutral feet during bare-foot single leg stance.

a) $H_{1} = TTBmin_{pronated} > TTBmin_{neutral} > TTBmin_{supinated}$

2) H1 = Pronated feet will have great maximal reach distance than both neutral and supinated feet.

a) $H1 = SEBTma_{xpronated} > SEBTma_{xsupinated} = SEBTma_{xneutral}$

3) There will be a positive relationship between FPI-6 scores and TTB mean minima.

4) There will be a positive relationship between cumulative FPI-6 scores and SEBT max reach scores.

5) There will be a positive relationship between TTB mean minima and SEBT max reach scores.

**Operational Definitions**

*Foot type:* Pronated (7-12), Neutral (1-4), Supinated (-2 - -12). (as defined by cumulative scores on the Foot Posture Index (FPI) scores).

*Balance Performance* – The ability of an individual to maintain their center-of-gravity within their base of support. TTB and SEBT will be used to assess balance performance. Low TTB mean and absolute minima indicate poor balance performance. Low SEBT reach is associated with poor balance performance.

*Traditional Measures of center of pressure* – Center of pressure mean and peak velocity, mean area, and max excursion.

*Time-to-boundary* - An estimation of the time it would take for the COP to reach the edge of the base of support if the COP were to continue on its trajectory at instantaneous velocity (Hertel, Olmsted-Kramer et al. 2006).

*Dominant leg:* Leg used to kick a soccer ball for maximum distance.

*Chronic Ankle Instability* – A score of less than 70% on the Functional Ankle Disability Index (FADI) or Functional Ankle Disability Index Sport (FADI-S)

**Assumptions**

1) All subjects will be truthful about their history of lower extremity injury.
2) All subjects will give maximal effort during trials
3) Force plate data collected using MotionMonitor software is reliable and valid.

**Delimitations**

1) Subjects will be excluded from the study who: a) have a history of lower extremity surgery b) have a history of concussions or vestibular disorders within the past 6 months c) have a history of visual disorders that cannot be corrected by glasses d) have an upper respiratory infection, inner ear infection, or head cold at the time of testing f) have a lower extremity injury in the past 6 months g) have chronic ankle instability or i) wear custom made orthotics regularly .
2) Subjects who currently participate (4 times or more/week) or have participated for more than 1 year in balancing sports (ballet, gymnastics, yoga, cheerleading) will be excluded from the study**.**
3) All single-leg static stance trials will be performed with eyes closed.

**Limitations**

1) Learning curve for balancing task may cause participants to improve with additional trials.
2) Weak core, hip, and leg muscles for stabilization may affect the balance of individuals during a single leg task.

3) Intrinsic joint laxity may be a confounding variable.

4) Speed of reach for SEBT trials cannot be controlled.

5) No Exclusion based on physical activity.

# CHAPTER II

# REVIEW OF THE LITERATURE

## Introduction

During athletic and recreational events, the ankle joint is the most commonly injured joint in the body because of the large mass it supports and the large amount of ground reaction forces it transfers (Brand, Black et al. 1977; Morrison and Kaminski 2007) It has been theorized that only 15-17%  of the population has a "normal" foot type, with perfectly neutral alignment (McPoil, Knecht et al. 1988; Smith-Oricchio and Harris 1990) There are three categories for intrinsic foot types; pronated, neutral, and supinated (Dahle, Mueller et al. 1991). Although several studies have reported finding no direct correlation between visual assessment of foot type and lower extremity injury (Dahle, Mueller et al. 1991; Barrett, JL et al. 1992), a few recent studies that used the Foot Posture Index-6 (FPI-6) to assess foot type, linked foot type to overuse foot and ankle injuries (Burns, Keenan et al. 2005; Cain, Nicholson et al. 2007). This suggests that the assessment of foot type may be important in identifying the athletes who may be at risk for sustaining an ankle injury.

Several studies have linked compromised balance performance with increased risk for acute ankle injury (Tropp, Ekstrand et al. 1984; Watson 1999; McGuine, Greene et al. 2000). It is possible that the link between foot type and ankle injury may be mediated by poor balance performance associated with the structural variation in foot types.  While there are several studies comparing balance performance between individuals with different foot types, the findings from such studies have been inconsistent possibly due to lack of valid and objective measures of foot type and poor sensitivity of the balance performance measures (Elveru, Rothstein et al. 1988; Picciano, Rowlands et al. 1993; Somers, Hanson et al. 1997; Razeghi and Batt 2002). Therefore, there is a need to further examine the effect of foot type on static and dynamic balance measures using valid and reliable measures of foot type, and a more sensitive balance performance measure.

The primary purpose of this study is to determine the effect of foot type on balance performance during static and dynamic balance performance tasks. This literature review will discuss basic foot anatomy and foot function, structural classification of foot type, postural control and balance measures, previous studies which have examined the difference in balance performance between individuals with varying foot type, measurement of foot type/posture, and measures of balance performance. The secondary purpose of this study is to discover if a relationship exists between SEBT, TTB and FPI-6 scores. This literature review will discuss each of these clinical tests in greater detail.

**Basic Foot Anatomy and Foot Function**

The foot is a complex structure comprised of more than 26 bones and 30 joint articulations (Morrison and Kaminski 2007). Although many functional motions take place at the foot and ankle, the two basic functions of the foot/ankle complex are 1) to adapt to ground surface while facilitating shock absorption, and 2) to function as a rigid lever to propel the body in space (Tiberio 1988). During the stance phase of ambulation the foot serves as an interface between the body and the ground, and thus the anatomical alignment of the foot may influence the body's ability to maintain the center of mass over the base of support during functional weight bearing activities (Levinger, Murley et al.). Stormont et al. (1985), explained the importance of the alignment of bones during this stance phase by demonstrating that, when fully loaded, the articular surfaces of the subtalar joint are the primary restraint for ankle inversion and eversion. Based on this knowledge, Guskiewicz et al. (1996) hypothesized that when the articular surfaces are not optimally aligned within the mortise ligamentous instabilities may occur during the loading and unloading of the ankle. Furthermore, since the foot is a relatively small base of support for the center of mass with a long mechanical lever arm, instability at the foot may result in greater sway of the rest of the body, and thus influence balance performance (Guskiewicz and Perrin 1996).

**Structural Classification of the Foot Type**

A foot type that is absent of bony deformities will have little issue with performing the basic foot functions of shock absorber and rigid lever (Tiberio 1988). However, most people are born with some sort of a foot structure abnormality, which alters how the foot functions during weight bearing tasks and, on a larger scale, how the body absorbs ground reactions forces through the kinetic chain (Smith-Oricchio and Harris 1990; McPoil and Hunt 1995; Guskiewicz and Perrin 1996). To understand how structural abnormalities may affect the foot and position of the body, we must first learn how the feet are classified. A variety of studies have attempted to classify the mechanical structure of the foot based on clinical evaluation. Though there are many classifications, the basic consensus is that there are three basic foot types; pronated, neutral, and supinated (Dahle, Mueller et al. 1991). Generally, pronated foot types are characterized by a flat medial longitudinal arch and calcaneal eversion and forefoot varus, whereas supinated foot types are classified as having a rigid high medial longitudinal arch with calcaneal inversion and forefoot valgus (Dahle, Mueller et al. 1991).

Pronated and supinated foot type results in alteration of the alignment of articular surfaces, causing abnormal joint arthrokinematics during weight bearing (Tiberio 1988). Specifically, with a pronated foot type the midtarsal joint unlocks during ambulation which allows the foot to act as a shock absorber, but may decrease the ability to act as a rigid lever (Levinger, Murley et al. ; Rome and Brown 2004). The supinated foot type results in a more rigid lever during the stance phase, thus compromising the ability to absorb ground reaction forces through the foot and adapt to surfaces. Additionally, the supinated foot with a rigid high arch results in decreased contact between the medial plantar surface and the ground, decreasing the afferent nerve activity from the plantar cutaneous receptors and thus possibly decreasing balance performance (Hertel, Gay et al. 2002; Olmsted 2004; Cote, Brunet et al. 2005; Tsai, Yu et al. 2006).

**Factors Influencing Balance Performance**

Balance is the ability of the body to maintain the center of pressure (COP) within the body's base of support (Guskiewicz and Perrin 1996). The COP reflects the mean position of the vertical projection of the center of mass (COM) of the body (Goldie, Bach et al. 1989) which is one way past researchers have quantified balance performance (Palmieri, Ingersoll et al. 2002). Balance is typically assessed by evaluating steadiness, symmetry, and dynamic stability of the center of mass of the body. Steadiness is defined as the ability to keep the COM of the body as motionless as possible. Symmetry is defined as the ability to distribute weight evenly between two feet in upright stance. And dynamic stability is defined as the ability to transfer the vertical projection of the COG around the base of support (Goldie, Bach et al. 1989).

The center of pressure (COP) is maintained within the body's base of support using a combination of vestibular, visual and proprioceptive feedback to the brain (Guskiewicz and Perrin 1996). Vision aids in balance by sending signals to the brain via the optic nerve, which give the body a reference point for where it is in space. Vestibular signals originate from the semi-circular canals deep within the ear, which also give the body a reference to where it is in space. Lastly, proprioceptive input comes from many different types of receptors in the skin, ligaments, and muscles. When these fibers are stimulated through movement, the signal helps the body to recognize where that limb is in space in relation to its surroundings (Guskiewicz and Perrin 1996). Two of the main mechanoreceptors involved in somatosensory feedback are Golgi tendon organs and muscle spindle fibers, which respond to tension and rate of tension applied to particular muscle during different tasks, respectively (Guskiewicz and Perrin 1996). When muscle spindles fire in response to the change of the rate of tension caused by ground reaction forces at the foot, it influences the balance posture of the rest of the body. The influence of the ankle on other parts of the body is evident in the kinetic chain theory which states that when stresses are placed on one segment of the body, adjacent segments must also react to maintain balance performance (Guskiewicz and Perrin 1996). Since the foot is the most distal segment of the body, ground reaction forces enter through the foot up through the ankle first, and then through the rest of the body (Guskiewicz and Perrin 1996).

**Balance Performance and Injury Risk**

While COP during a single leg stance is commonly used to assess balance performance, there are debates regarding the interpretation of the variables derived from the COP values. Some investigators consider higher COP excursions (both magnitude and velocity) to be associated with poor balance (Tropp, Ekstrand et al. 1984; Guskiewicz and Perrin 1996; Watson 1999; McGuine, Greene et al. 2000) while others suggest that increased variability is a natural human response (Newell, REA et al. 1993; Beynnon, Renstrom et al. 2001; Ross and Guskiewicz 2004; Brown and Mynark 2007). The studies that linked greater postural sway with an increased risk for ankle injury support the first view (Tropp, Ekstrand et al. 1984; Watson 1999; McGuine, Greene et al. 2000). Tropp et al. (Tropp, Ekstrand et al. 1984) measured COP using force plates during the preseason for soccer players. The study demonstrated that the athletes with higher postural-sway values had higher risk of ankle sprain compared to those with lower postural sway. Similarly, Mcguine et al. (McGuine, Greene et al. 2000), measured postural sway in high school basketball players, and demonstrated that athletes with increased postural sway were at an increased risk for ankle injury than those with normal postural sway. Watson et al. (Watson 1999), also demonstrated that individuals who were unable to maintain a single leg stance for 15 seconds suffered from a greater number of acute ankle sprains than athletes who were able to maintain balance for 15 seconds. Unlike these studies, a study by Beynnon et al. (Beynnon, Renstrom et al. 2001) did not demonstrate a relationship between COP excursions and injury risk, most likely due to sampling only soccer, lacrosse, and field hockey players. Therefore, the previous literature suggests that poor balance performance may be indicative of an ankle injury risk factor.

**Effects of Foot Type on Balance Performance**

To date, only a few studies have been conducted to examine the effects of foot type on balance performance during a single-leg balance task (Hertel, Gay et al. 2002; Olmsted 2004; Cote, Brunet et al. 2005; Tsai, Yu et al. 2006). Hertel et al. (2002) compared a single-leg balance performance in young adults with different foot types. In this study, foot type (pes cavus, neutral, and pes planus) was classified by visual assessment in non-weight bearing position described Root et al. (1977). The study demonstrated that individuals with pes cavus foot had greater center of pressure (COP) excursions than individuals with both planus and neutral feet. This finding was attributed to lack physical contact between medial aspect of foot and the forceplate due to the high arch. The lack of physical contact indicates less afferent input from the plantar cutaneous receptors, resulting in decreased feedback from somatosensory organs, contributing to overall decrease in balance performance (Hertel, Gay et al. 2002). While the study demonstrated an important link between foot type and balance performance, the limitation of the study was that the foot type was assessed in a non-weight bearing position, when the balance tasks were performed in a weight bearing position, providing little clinical application. The forefoot and rearfoot alignment angles differentiating the groups had a large standard deviation which overlapped between groups, indicating that groups may not be clearly different. Another limitation of the study was that there are debates regarding whether or not the COP excursions indicate impaired balance performance (Hertel, Gay et al. 2002).

In contrast to the findings from the study by Hertel et al., another study that assessed the effect of foot type on static and dynamic balance performance with orthotic intervention did not find any significant difference in static balance performance between individuals with different foot types, but found difference in dynamic balance (Olmsted 2004). In this study, the foot type was classified by the visual assessment proposed by Dahle et al. (1991), grouping feet into pes planus, rectus and cavus. The static balance was assessed using COP area and velocity excursions during a single-leg stance task, while the dynamic balance was assess using the Star-Excursion Balance Test (SEBT). For the intervention using orthotics a foot scanner was used to analyze and customize semi-rigid orthotics for each individual. The orthotics were worn for 4 weeks for at least 4 hours a day. The study showed no significant difference between foot type and COP excursions during a single-leg static stance. During the SEBT, the pes cavus group had greater reach in all directions. This may possibly be due to lack of physical contact between medial aspect of foot and the forceplate, allowing for greater reach. The study also demonstrated that the orthotic intervention resulted in improved static and dynamic balance in the pes cavus foot group. Similarly to the study by Hertel et al. (2002), this study was limited because it assessed the foot type in a non-weight bearing position for a weight bearing task (Olmsted 2004).

Similar to the findings in the study by Olmsted et al. (2004), when comparing the effects of pronated and supinated foot types on static and dynamic postural stability, Cote et al. (2005), observed no significant different between dominant limb foot type for static measures, and greater reach distance in the supinated foot type. Foot type (pronated, neutral, supinated) was classified using the navicular drop test. Subjects were tested for static balance performance on a Chateex balance system during a single-leg stance balance task with eyes open and eyes closed. Dynamic balance performance was assessed using the SEBT. No differences were found in static stance measure of COB and postural sway. However, during the dynamic task, supinators had greater reach in lateral and posterolateral directions. This finding was attributed to increased mechanical support to the medial aspect of the foot specific to the supinated foot type, allowing for greater deviations around the base of support. This study utilized the navicular drop for foot classification. The navicular drop test is not the best measure of foot type because it has low intratester and intertester reliability, and furthermore grouping foot type into three categories based on one measure may not be a valid functional measure of foot type (Razeghi and Batt 2002; Redmond, Crosbie et al. 2006).

Contrarily to the aforementioned studies, the most recent study to observe the effects of foot type on balance performance found that the supinated foot type had greater maximum displacement than the pronated foot type in the medial/lateral direction (Tsai, Yu et al. 2006). In this study, foot type (pronated, supinated, neutral) was classified using the weight bearing measures outlined by Jonson and Gross, which is a reliable measure of foot classification but has not been validated (Jonson and Gross 1997; Razeghi and Batt 2002). Clinical assessment of balance performance was assessed during a single-leg stance with eyes closed. Normalized mean COP velocity, and maximum displacement of COP in AP and ML directions were used to assess balance performance across all participants. The supinated group had significantly greater center-of-pressure maximum displacement in the anterior/posterior and medial/lateral direction than neutral group, and also displayed greater mean velocity in the anterior/posterior direction. The pronated group had significantly greater standard deviation and maximum displacement in the anterior/posterior direction than neutral. Comparing foot types to each other, the supinated foot type had greater max displacement in the medial/lateral direction than pronated group. It was proposed that pronated foot type may have more advantage in maintaining balance performance in the medial/lateral direction because of the wider base of support (flat foot).

These studies indicate that the association between foot type and balance performance is still inconclusive (Hertel, Gay et al. 2002; Olmsted 2004; Cote, Brunet et al. 2005; Tsai, Yu et al. 2006). Hertel et al. (2002) and Tsai et al. (2006) observed a significantly greater COP excursion in the supinated foot type compared to the pronated foot type during static single-leg balance. Cote et al. and Olmsted et al. (Olmsted 2004; Cote, Brunet et al. 2005), observed no significant differences between foot type and measures of static postural sway during a single-leg balance task. However, both studies observed greater values for supinated foot type during the SEBT in at least two directions. The great variation in methods for these studies indicates the need for a more sensitive measure of balance performance and a more valid foot classification system.

**Methodological Considerations**

*Classification of Foot Type*

To study the effects of foot type on any outcome variables, there must be a valid and reliable way to classify foot type (Razeghi and Batt 2002).There are three generally accepted categories for intrinsic foot types; pronated, neutral, and supinated (Dahle, Mueller et al. 1991; Razeghi and Batt 2002). Many techniques have been proposed for assessing foot type including visual non-quantitative inspection, anthropometric values, footprint parameters, and radiographic evaluation (McPoil and Hunt 1995; Razeghi and Batt 2002; Redmond, Crosbie et al. 2006). If there is a “Gold-standard” for foot classification, it would be radiographic measures (Razeghi and Batt 2002). However, radiographic measures are time-consuming, expensive, and involve subject’s exposure to radiation. Measurement of joint angles using goniometers are more practical than radiographic measures but have poor reliability (Redmond, Crosbie et al. 2006).The navicular drop is one method used in some studies to classify foot type (Cote, Brunet et al. 2005; Redmond, Crosbie et al. 2006). The advantage of navicular drop is that it is a fast and valid measurement of arch height. However, the disadvantage of navicular drop is that it only uses one measure to assess a dynamic structure (the foot), and it demonstrates poor to moderate intratester and intertester reliability ICC (0.33 to 0.79) (Picciano, Rowlands et al. 1993; Vinicombe, Raspovic et al. 2001; Razeghi and Batt 2002; Redmond, Crosbie et al. 2006). Therefore, navicular drop may not provide an accurate measure of foot function during dynamic motion (Menz 1998). Another foot classification method proposed by Jonson and Gross (Jonson and Gross 1997) has moderate to high reliability (ICC .65-.97), but has not been validated against any other measure of foot classification (Razeghi and Batt 2002).

More recently a validated foot scoring system called the Foot Posture Index 6 (FPI-6) developed by Redmond et al. (2006), has been increasingly used to categorize subjects by foot type (Burns, Keenan et al. 2005; Redmond, Crosbie et al. 2006; Cain, Nicholson et al. 2007; Cornwall, McPoil et al. 2008; Redmond, Crane et al. 2008). The FPI-6 assessment takes measurements in a more functional weight bearing posture and assesses the foot based on a six-factor scoring system **(Appendix 1)** (Redmond, Crosbie et al.

2006; Redmond, Crane et al. 2008). The six factors are represented on a standardized checklist for scoring and are 1) talar head palpation 2) curves above and below the malleoli 3) calcaneal inversion/eversion 4) talo-navicular congruence 5) medial arch height and 6) forefoot abduction and adduction. Each factor is scored on the checklist with a possible +2 or -2 points, contributing to a cumulative score. Based on the cumulative score, the subjects will be classified into 5 foot types: highly pronated 10-12, pronated 6-9, neutral 0-5, supinated -1- -4, highly supinated-5 - -12.

The FPI-6 is both a valid and reliable measure of foot type. The reliability and validity of the assessment was originally tested using an eight factor scoring system (FPI-8) (Redmond, Crosbie et al. 2006). Two components of the test (lateral border congruence and Helbing's sign) were dropped from the test because of low reliability scores, which resulted in FPI-6. The validation of the FPI-6 scores were then conducted by comparing the measures against a three-dimensional model of the foot obtained from Fastrack, a skin-mounted electromagnetic tracking sensor system (Redmond, Crosbie et al. 2006). The FPI-6 reflects the variations in posture detected by the electromagnetic measure. (Intra-class coefficients = .62-.91). Also, the FPI-6 has been shown to have high intratester reliability (.753-.985) (Cornwall, McPoil et al. 2008). The lower intratester reliability (.753) was performed by a physical therapy student with no experience evaluating feet, while the other two more experienced raters in the study showed higher ICC values (.985). One possible limitation with the FPI-6 is that composite scores will reflect many possible combinations of the 6 factors, allowing the user to possibly interpret results differently (Redmond, Crosbie et al. 2006). However, overall the FPI-6 is a reliable and valid weight bearing classification of foot type. Investigators described the

FPI-6 as a “quick, simple, multidimensional assessment of the static foot as an indication of the dynamic foot during gait (Teyhen, Stoltenberg et al. 2011).” Based on these previous studies, the FPI-6 will be a good instrument for the assessment of foot type during a single leg balance task.

It is recommended that new raters gain experience using the FPI-6 on at least twenty subjects before using their values for further analysis. In addition, a few practice trials before each testing is recommended for the rater to complete before each screening period (Cornwall, McPoil et al. 2008).

*Consideration for subject selection*

Previous literature suggests that the inclusion criteria for subjects must be carefully considered for a study examining foot type and balance performance (Hertel, Gay et al. 2002; Olmsted 2004; Cote, Brunet et al. 2005; Tsai, Yu et al. 2006). Hertel et al. (2002), ensured that potential participants were free of cerebral concussions, vestibular disorders and lower extremity orthopedic injuries within the 6 months before testing. Olmsted et al. (2004), were more general in their exclusion criteria and simply required that the participant has no lower extremity musculoskeletal injury history. Contrarily, Cote et al. (2005), required that all participants must have no reported lower extremity injuries in past 6 months, no history of surgery to lower extremity, no history of cerebral concussions or visual/vestibular disorders, no inner ear infection, and no upper respiratory infection or head cold at the time of the study. Lastly, Tsai et al. (2006), were the most specific in their inclusion criteria requiring that participants must have no reported lower extremity injuries in past 6 months, left and right symmetric structure, no neural or vestibular disease or lower extremity arthritis, no pain present in lower extremities at time of testing, and no drugs taken within 24 hours that may affect balance performance (alcohol, sedatives, cold remedies, stimulants). In addition to these criteria, participants who engaged in exercise or training that might require good balance performance (ballet, gymnastics, tai chi) during 1 year prior to participation and participants engaged in prior listed activities for more than 1 year in the past 10 years were excluded. Additionally, an online assessment form called the Functional Ankle Disability Index, is used to determine subjects at risk for Chronic Ankle Instability (Hale and Hertel 2005). A study by Van Wegen (2002) found no differences between age group (24-38 years of age) and (55-69 years of age) on time-to-boundary measures in a double leg stance. However, the older age group exhibited greater COP variability, which indicated that the elder population may exhibit poor balance performance compared to young individuals (van Wegen, van Emmerik et al. 2002).

*Assessment of Balance Performance*

Balance performance is typically measured using a force place. The forces and moments measured by the force plate are used to calculate the center of pressure (COP) (Guskiewicz and Perrin 1996; Palmieri, Ingersoll et al. 2002). Traditional ways to analyze the COP data include looking at maximum excursions and peak velocity, as well as mean velocity and area. Mean COP velocity measures the mean excursions about the COP in both the medial/lateral and anterior/posterior direction. On the other hand, COP area measures the total amount of area covered by the linear displacement about the COM during the trial. Lastly, peak velocity measures the maximum velocity during the trial, and max excursion measures the maximum excursion in both the anterior/posterior and medial/lateral directions that occurs during the trial (Goldie, Bach et al. 1989).

The duration for a single-leg stance trial commonly used in the literature is 10-20 seconds for traditional COP measurements (Carpenter, Frank et al. 2001). For the previous studies on foot type and postural sway, data were typically gathered at a frequency between 15-50 Hz for 10-15 seconds (Hertel, Gay et al. 2002; Olmsted 2004; Cote, Brunet et al. 2005; Tsai, Yu et al. 2006). For time-to-boundary, data were sampled at 50 Hz for a 10 second single-leg balance trial (Hertel, Olmsted-Kramer et al. 2006; McKeon and Hertel 2007; McKeon and Hertel 2008; Hoch and McKeon 2011).

A more novel method of analyzing the COP called time-to-boundary (TTB) is gaining popularity in the balance literature. TTB is an estimation, using traditional COP measures, of the time it would take for the COP of any given subject to reach the edge of the base of support (the borders of the feet) if the COP were to continue on its trajectory at a constant instantaneous velocity. The time-to-boundary (TTB) is calculated by dividing the distance between the COP and the border of the foot the COP is moving towards by the instantaneous COP velocity. The point at which a subject is at greatest risk for falling outside of the foot boundary is called a minima. Through a testing, there will be a series of minima, or lowest values. A low TTB minima value indicates greater postural instability because the subject will have less time to execute a postural correction due to the COP being close to going outside the edge of the base of support (McKeon and Hertel 2007). The standard deviation of the minima indicates the number of solutions used for an individual to maintain single-leg stance based on the boundaries of support for that individual (Hertel and Olmsted-Kramer 2007; Hoch and McKeon 2011)

Because TTB uses COP measurements in a way that incorporates both spatial (displacement) and temporal (velocity and acceleration) aspects of posture, it is thought to have more clinical applicability than previous standard measures of COP (Haddad, Gagnon et al. 2006; Hertel, Olmsted-Kramer et al. 2006; Hertel and Olmsted-Kramer 2007). TTB has levels of reliability that are consistent with traditional COP measures of mean velocity (.34 - .87). But there is a weak correlation between TTB and COP measures, indicating that both measure a different aspect of balance performance (Hertel, Gay et al. 2002). To date, TTB measures have detected postural deficits in geriatric adults and patients with Parkinson's disease (Wegen and Van Emmerik 2001; Van Emmerik and Wegen 2002; Wegen and Van Emmerik 2002). Also, female subjects with CAI demonstrated a significant difference in five of six measures of TTB, compared to one of eight traditional measures of COP during a single-leg stance (Hertel and Olmsted-Kramer 2007). TTB measures were also observed to be significantly altered for subjects in a state of plantar hypoesthesia compared with the same subjects in a normal state (McKeon and Hertel 2007). Lastly, a recent study examined the effects of chronic ankle instability (CAI) compared to healthy individuals on TTB measures and found that the CAI group has significantly lower TTB measures (Hertel and Olmsted-Kramer 2007; McKeon and Hertel 2008). Contrarily, two studies found no significant differences in balance performance between those with chronic ankle instability and healthy individuals using traditional measures of COP (Isakov and Mizrahi 1997; Baier and Hopf 1998), indicating that the TTB may be a more sensitive analysis of balance performance. One disadvantage of TTB is that there is limited literature available since it is a new measure of balance performance.

Another assessment of balance performance, the Star Excursion Balance Test (SEBT), has been used in recent literature as a dynamic, functional assessment of balance performance. The advantage of the SEBT, as described by Olmsted et al. (2002) is that it may be better than static postural-control assessment to determine functional deficits. The SEBT may be sensitive enough to "detect possible deficits in healthy athletes and therefore predict future potential injury risk.(Munro and Herrington)" In a study by Plisky et al. (2006)., there was a correlation between decreased SEBT performance in three directions and lower extremity injury in high school athletes. Additionally, the SEBT has detected differences in balance performance between those with and without chronic ankle instability and fatigue (Olmsted, Carcia et al. 2002; Gribble, Hertel et al. 2004). The SEBT has demonstrated moderate intrasession reliability (0.67 – 0.87 ICC) (Kinzey and Armstrong 1998). Hertel et al. (2000) established the intratester and intertester reliability of the SEBT at an ICC of 0.82 to 0.96 and 0.81 to 0.93, respectively. The original SEBT proposed six practice trials followed by three test trials in all eight directions (Hertel, Miller et al. 2000), making for a long and tedious testing session. Recently a shortened version of the SEBT has been used to assess ankle injury risk (Plisky, Rauh et al. 2006). In this shortened version, the reach is shortened to three directions (anterior, posterior-medial, posterior-lateral). Also, a few studies have suggested that four practice trials are sufficient to eliminate the learning effect (Robinson and Gribble 2008; Demura and Yamada 2010). The effect of foot type on the SEBT has been studied previously by Gribble et al., (2003) using foot classification by Root et al. (1977), and found no significant difference in reach scores across foot type. There remains a need to assess the SEBT across foot type using a more functional foot classification system like the FPI-6.

# CHAPTER III

# METHODOLOGY

## Subjects

Sixty-one (20 pronated, 21 neutral, and 20 supinated foot) healthy participants ranging from 18-38 years of age participated in our study. The participants were excluded from the study if they had: 1) history of lower extremity surgery, 2) a history of concussions or vestibular disorders within the past 6 months, 3) a history of visual disorders that cannot be corrected by glasses, 4) upper respiratory infection, inner ear infection, or head cold at the time of testing, 5) lower extremity injury in the past 6 months, 6) chronic ankle instability. In addition, participants who already wear orthotics regularly, or participants who currently participate (4 times or more/week) or have participated for more than 1 year in balancing sports (ballet, gymnastics, yoga, cheerleading) were excluded from the study (Hertel, Gay et al. 2002; Olmsted 2004; Cote, Brunet et al. 2005; Tsai, Yu et al. 2006). We excluded subjects 51 and 52 because they scored a six on the FPI-6 test, which we pre-determined as an exclusion criteria. Also, subject 3 was excluded as an outlier for the study. An error was made during data collection with the force plate axis set-up and could not be rectified.

## Measurement and Instrumentation

Foot Posture Index 6 (FPI-6) was used to classify foot type **(Appendix 1)**. The FPI-6 allows the researcher to group participants into 5 categories based on a 6-factor point system. First, a primary researcher and a research assistant used the FPI-6 to screen all participants. The intratester reliability of the primary researcher was established using test/re-test design on 13 subjects (26 feet). The data were analyzed using SPSS, and a Kappa measure of agreement value was derived for each category of the FPI-6 (**Table 4**). For intrarater reliability, the measure of agreement for placing participants into the proper foot category was .636, which is "good agreement." One factor of the FPI-6, "forefoot abduction/adduction" received a Kappa score of .164 which is "poor agreement." After reviewing the data, this was most likely due to an outlier who was rated -1 for both feet during the first test, and then rated 1 for both feet during the second test. This was most likely due to simple abduction of the feet by external rotation at the tibiofemoral joint, rather than a permanent structural deformity of the foot. The intertester reliability of the primary researcher to the assistant was also established prior to research on 5 subjects (10 feet total). The data were analyzed using SPSS, and a Kappa measure of agreement value was derived for each category of the FPI-6 (**Table 4**). During the testing, intertester reliability for foot category placement on 39 participants was (Kappa = .757) For the screening assessment, participants were instructed to stand on the floor in a double-leg weight-bearing stance while the researcher inspects 6 structural points: 1) talar head palpation, 2) curves above and below the malleoli, 3) calcaneal inversion/eversion, 4) talo-navicular congruence, 5) medial arch height, and 6) forefoot abduction/adduction. The investigator assigned a point score ranging from -2 to +2 (-2 ,-1 ,0 ,1 ,2) for each factor. A more negative score indicates a supinated foot characteristic, while a more positive score indicates a pronated foot characteristic. The cumulative score was calculated as a sum of the score from each factor. Based on the cumulative score, FPI-6 classifies the participant into the following 5 categories: Highly pronated (10-12+), pronated (6-9), neutral (0-5) supinated (-1- -4) and highly supinated (-5 - -12) (Redmond, Crosbie et al. 2006; Redmond, Crane et al. 2008). In this study, participants were classified in to the pronated group if they have highly pronated or pronated foot type (7-12). The participants were classified in to the supinated group if they have highly supinated and supinated foot type (-2 - -12). The participants with neutral foot were classified in to the neutral group (1-4). To create a larger effect size, participants who scored a cumulative -1, 0, or a 5, 6 by the primary researcher were left out of the study.

Leg length was measured and recorded in centimeters for each participant in order to normalize Star-Excursion reach data. Leg length was measured according to the protocol outlined by Gribble et al. (Gribble and Hertel 2003) with the participant lying supine. A tape measure was used to quantify the distance from the base of the anterior superior iliac spine (ASIS) to the center of the ipsilateral medial malleolus for each limb.

Time-to-boundary (TTB) measure was used to assess balance performance. TTB represents the time it would take for the center of pressure to fall outside of the boundary if it were to continue on its trajectory, and is calculated from the position of COP relative to the boundaries of the foot and the instantaneous velocity of a center-of-pressure COP in medial-lateral and anterior-posterior directions at each data point. A lower TTB absolute minima value is indicative of postural instability. In this case the low number represents that the individual would have less time to respond to the COP moving outside of the base of support (Hertel, Olmsted-Kramer et al. 2006). The COP measurements were sampled using a force plate (model 4060-NC, 300X400 mm; Bertec Corp, Columbus, OH) at a sampling frequency of 50 Hz using Motion Monitor software (version6.74; Innovative Sports Training, Inc, Chicago, IL). The force plate was calibrated prior to testing. The x-axis of the force plate was defined along the long axis (anterior-posterior direction), and the y-axis was defined along the short axis (medial-lateral direction) of the force plate. A piece of athletic tape was used to mark the mid-lines of the force plate in the x and y direction. The participants stood facing the positive x-axis of the force plate. Therefore, the COP movement along the x-axis represent the movement in the anterior-posterior direction, and the y-axis represents the movement in the medial-lateral direction.

**Procedures**

*Screening procedure*

The potential participant was screened for the inclusion and exclusion criteria. If the participant met all criteria, he/she proceeded to fill out the FADI online assessment for chronic ankle instability. The assessment was conducted on the dominant foot, determined as the foot participant uses to kick a soccer ball. The participants who met the study and group criteria were scheduled for the testing session.

*Testing procedures*

Upon arrival to the Sports Medicine Research Laboratory, all potential participants read and signed an informed consent form approved by the University Institutional Review Board. The participant's body mass, height and leg length were measured and recorded. The participant's foot type was assessed standing on the floor in a comfortable stance while the researcher visually inspected the foot. The researcher then assigned a value to six factors as outlined by the FPI-6 **(Appendix 1)**. Based on a cumulative score ranging from (-12-12), participants were categorized and assigned to one of three groups: pronated (7-12), supinated (-2 - -12), or neutral (1-4). The participant was then tested by a second tester to establish reliability. 39 of the 61 subjects were tested by an IRB-approved second rater. Then, the rectangular border of the bare foot was measured by using a custom-made measuring device **(Figures 1.A-D)**. The device is a thin wooden panel that is bordered with two adjacent pieces of wood at a 90 degree angle to each other. A piece of paper was placed on the device, then the participant placed their foot against the adjacent borders of the device. The researcher then marked the most anterior and medial (left foot) or lateral (right) portion of the foot, and asked the participant to remove the foot from the device. The researcher then used a straight edge to draw a line on the paper crossing the most anterior and medial/lateral portion of the foot and mark the mid-points of the medial-lateral and anterior-posterior borders. The mid-point measurements were then recorded on a form for TTB data. The researcher then asked the participant to step back into the device to make the foot where it corresponds to the mid-points in the medial-lateral and the anterior-posterior directions. The mid-points were then used to align the foot on the force plate in the same location for repeated trials.

After the foot measurement, a paper was drawn out of a bucket to determine the order of testing. If the participant drew the Star Excursion, they would test with that first, if they drew the single-leg balance task, they would perform that test first. The order was determined by simple random assignment without replacement.

For the single-leg balance task, the participant was instructed on how to perform the task. For all balance trials, the participant placed the stance foot in the same position on the force plate by aligning the mid-point marks on the foot with the mid-points on the force plate. The participant was instructed to place his/her hands on bilateral ASIS while closing his/her eyes. The non-dominant limb was raised 1-2 inches off the ground with flexion only at the knee. Participant performed a 10 second practice trial to become accustomed to the testing procedure. The participant then performed three consecutive trials of a single-leg balance task in bare feet. The trial began when the participant acknowledged being ready in a single-leg stance. The data was collected from the force plate for 10 seconds. When the 10 seconds were finished, the participant was notified by the researcher and placed the non-dominant leg down in a comfortable stance. Fifteen seconds were provided between trials to minimize fatigue (Olmsted, Carcia et al. 2002). The trials were discounted and repeated if: the non-dominant limb touched the ground or dominant limb at any point, the dominant limb shifted from original position during measurement, either hand left its position from the ASIS, or the participants opened their eyes (Hertel and Olmsted-Kramer 2007).

The Star-Excursion test was set-up using three tape-measures with the two posterior lines at a 135 degree angle from the anterior line, and 90 degrees from each other (**Figure 4)** increments from the center of the grid, as recommended by Plisky et al. (Plisky, Rauh et al. 2006). The instructor first demonstrated and verbally instructed the subjects on the proper and safe technique for this task. The subject performed four practice trials reaching in three directions to become familiar with the task, as recommended by Munro et al. and Robinson et al. (Munro and Herrington ; Robinson and Gribble 2008). The subject began  by performing four reaches in the anterior direction (Olmsted, Carcia et al. 2002), subsequently followed by four reaches in the posteriomedial direction, and posteriorlateral direction. The subject stood with the most distal portion of the dominant foot on the intersection of lines. With the opposite leg, the subject  touched the most distal part of their foot to the furthest point possible on the lines, and then returned to a bilateral stance while maintaining equilibrium. For the trials, three reaches were recorded and marked by erasable marker on the tape measure lines for each of the three directions. Direction was counterbalanced to control for learning effect. Trials were discarded and repeated if the subject 1) did not touch line with the reach foot while maintaining weight bearing on the stance leg, 2) lifted the stance foot from the center grid, 3) lost balance at any point in the trial, 4) did not maintain start and return positions for one full second, or 5) used the reach foot to place weight on it for support (Olmsted, Carcia et al. 2002).

**Data reduction**

TTB was calculated from the dimension of the foot and the instantaneous position and velocity of the COP **(Figure 2)**.

The COP data was filtered using a $4^{th}$ order zero-lag low-pass Butterworth filter with a cut off frequency of 5 Hz (Hertel, Olmsted-Kramer et al. 2006; Tsai, Yu et al. 2006). Using the filtered data, COP velocity in the medial/lateral (ML) and anterior/posterior (AP) directions was calculated as a first derivative of the position data. If the COP is moving medially, the distance between COP ML and the medial rectangular border of the foot was calculated. This distance was then divided by the corresponding instantaneous velocity of COP ML, calculating the time it will take the COP ML to reach the medial border of the foot if it were to continue moving in the same direction with no change in velocity. When the COP ML is moving in a lateral direction, the distance between COP ML and the lateral border of the foot was calculated and divided by the corresponding instantaneous velocity of the COP ML. A time series of corresponding

TTBAP measures was similarly generated by estimating the time it will take COP AP to reach the anterior or posterior rectangular boundary of the foot.

Each TTB time series contains multiple peaks and valleys. Valleys represent TTB minima (**Figure 3)**. The derivative of the TTB was calculated to identify the minima. Once the TTB minima were identified, absolute minimum was calculated in the ML and AP directions for each trial. An average of the TTB minima was calculated across all minima during each trial to determine the mean TTB. Lastly, the standard deviation of the minima was calculated, indicating the number of solutions used for individual to maintain single leg stance based on the boundaries of support for that individual (Hertel and Olmsted-Kramer 2007; Hoch and McKeon 2011).

The star-excursion test data was marked on the measuring tape for each reach direction (cm). The max reach distance was recorded in each of the three directions and averaged across the trials. The reach distance was normalized to leg length by dividing the max reach distance average (cm) by the leg length (cm) and multiplying by 100 (Gribble and Hertel 2003).

**Data Analysis**

The data was analyzed using nine one-way ANOVA to compare the nine dependent variables (for all dependent variables in both the medial-lateral direction and anterior-posterior direction, and the star-excursion max reach in three directions) between individuals with pronated, neutral, and supinated foot types. A Tukey post hoc analysis was used to determine significant differences between groups. Secondly, a bivariate correlation analysis was run between FPI-6 cumulative scores, SEBT max reach scores and TTB minima.

Based on the previous study that compared TTB measures in individual with and without chronic ankle instability (Hertel and Olmsted-Kramer 2007), the effect size for the group comparison of the absolute minima TTBML was 0.74. In order to achieve a statistical power of .80 to demonstrate a statistically significant group difference in absolute minima of the TTBML at an alpha level of 0.05, a minimum of 6 subjects were needed. Therefore a total of 20 subjects were enrolled in the pronated and supinated groups, and 21 in the neutral group to ensure enough power. An a priori alpha level will be set at .05. The data was analyzed using SPSS 16 statistical software (SPSS, Inc. Chicago, IL).

# CHAPTER IV

## RESULTS

The mean across all subjects for time-to-boundary (TTB) absolute minima was (0.048± 0.067 secs) in the medial-lateral plane and (0.696 ± 0.291 secs) in the anterior-posterior plane. For TTB mean minima the mean across all subjects was (0.519 ± 0.195 secs) in the medial-lateral plane and (2.47 ± 0.933 secs) in the anterior-posterior plane. For standard deviation of TTB, the mean across all subjects was (0.641 ± 0.299 secs) in the medial-lateral plane and (1.60 ± 0.711 secs) in the anterior-posterior plane. The mean across all subjects for SEBT maximum reach was (74.2 ± 6.80 cm) in the anterior direction, (101.8 ± 10.5cm) in the posteromedial directions, and (94.3 ± 12.2cm) in the posterolateral direction.

There was a significant interaction between foot type and mean minima in the medial-lateral direction ($F_{2,58}$=3.504, $P$ = .037) **(Table 2).** Using Tukey post-hoc analysis, we observed that individuals with pronated foot type had significantly greater TTB mean minima (better balance) compared to individuals with neutral foot type ( 95% CI: LB:0.0043 UB: .0853, $P$ = .029). However, there were no significant differences in time-to-boundary mean minima in the anterior-posterior ($F_{2,58}$=0.410 , $P$ = 0.665) direction between individuals with pronated (PRO) , neutral (NEU), and supinated (SUP) foot type.

There were no significant differences in time-to-boundary absolute minima in the anterior-posterior ($F_{2,58}$=0.100, $P$ = .905) or medial-lateral ($F_{2,58}$=2.536, $P$ = .088) directions between foot type **(Table 2)**. Similarly, there were no significant differences in

TTB standard deviation in the anterior-posterior ($F_{2,58}$=1.212, *P* = .305) or medial-lateral ($F_{2,58}$=2.961, *P* = .060) direction between individuals with PRO, NEU, and supinated foot types **(Table 2)**.

There were no significant differences in star excursion maximum reach in the anterior ($F_{2,58}$=.119, *P* = .888), posterior-medial ($F_{2,58}$=.1.281, *P* = .286), or posterior-lateral ($F_{2,58}$=.1.507, *P* = .230) directions between foot type groups **(Table 3).**

There was a statistically significant positive correlation between FPI score and TTB standard deviation of the minima in the medial-lateral direction ( r = .266, $R^2$ = .07 *P* = .038 ). While this indicates that increase in foot score is associated with greater TTB standard deviation minima scores in the medial-lateral direction, the low Pearson correlation coefficient ( r = .266) and $R^2$ value ($R^2$ = .07) indicates that there is little clinical relationship between the two variables **(Table 5).** There were no statistically significant positive correlations between FPI score and TTB mean minima, TTB absolute minima, or TTB standard deviation in the anterior-posterior direction.

There were no statistically significant positive correlations between FPI score and SEBT max reach in anterior, posteromedial, or posterolateral direction **(Table 6)**. Similarly, there were no statistically significant correlations between SEBT max reach in all directions and TTB minima values **(Table 7)**.

# CHAPTER V

## DISCUSSION

The purpose of our study was to determine if single-leg balance performance differs among individuals of different foot types using time-to-boundary (TTB) and Star Excursion Balance (SEBT) tests and also to determine if there is a relationship between FPI-6 scores, TTB mean minima and SEBT scores. Our results indicated that individuals with pronated feet (PRO) exhibited better balance performance than those with neutral feet (NEU) in the medial-lateral (ML) plane in one of the six measures of balance performance. However, there was no difference between foot type in the other five measures. Therefore, we found that balance performance was not significantly affected by foot type. We also found that dynamic balance performance, as assessed using the SEBT, was not affected by foot type.

Three variables calculated from TTB measures are absolute, mean, and standard deviation of the TTB. TTB is an estimation, using traditional center of pressure (COP) measures, of the time it would take for the COP of any given subject to reach the edge of the base of support (the border of the foot) if the COP were to continue on its trajectory at a constant instantaneous velocity. The absolute value of TTB minima and mean of the TTB minima are both indicative of the time the individual has to make postural corrections before falling outside the base of support. A higher absolute mean TTB minima is considered to indicate better balance performance in that it gives the subject more time to make corrections. On the other hand, standard deviation of the TTB minima scores represents variability in the signal and is indicative of a greater number of solutions available to maintain balance (Hoch and McKeon 2011). A person with more solutions available for balance will be better able to adapt to a variety of situations which is exemplified in sporting activities in a variety of settings. For example, in soccer we know that it takes practice and repetition in order to strike the ball precisely in the correct spot in order to make it travel in the desired direction, height, and velocity. Due to the fact that the ball is moving in a variety of unpredictable ways, a soccer player must have multiple solutions available in order to strike the ball with accuracy in an ever changing environment, ultimately providing a better outcome (direction, accuracy, etc.). Similarly, an individual who has a greater number of solutions while balancing will be able to adapt better to a variety of situations than an individual with a limited number of solutions. Therefore, greater variability (higher standard deviation of the TTB minima) represents a less constrained sensorimotor system with more strategies available to help maintain balance, and thus superior balance performance (Hoch and McKeon 2011).

While there are several studies that investigated the effects of foot type on balance performance, the uniqueness of this study was that it used Foot Posture Index-6 (FPI-6) foot classification to assess foot types using both a laboratory (TTB) and clinical (SEBT) measure to assess dynamic balance performance. We used the FPI-6 because it has been shown to be a valid and reliable weight bearing assessment of foot posture that may be clinically useful and offer a distinct advantage to other foot type assessments (Redmond, Crosbie et al. 2006; Cornwall, McPoil et al. 2008; McKeon and Hertel 2008; Redmond, Crane et al. 2008) Based on FPI-6 scores (range: -12 to +12), participants with scores above 7 were considered to have a pronated foot type, 1-5 were considered to have neutral foot type, and lower than -1 were considered to have a supinated foot type. To ensure separation between groups, we excluded participants with cumulative FPI-6 scores that were "in-between" foot type. Specifically, any subject who scored a "6" or a "0" were excluded from the study.  We also used TTB over traditional measures because is believed to be a more sensitive measure of dynamic balance performance, which may have more clinical applicability (Hertel and Olmsted-Kramer 2007).

We hypothesized that the PRO group would have better balance performance than NEU and SUP groups due to a wider base of support typical of pronated feet (Tiberio 1988; Tsai, Yu et al. 2006). Pronated feet generally have mobile transverse carpal joints (Tiberio 1988). While the bones in the arch being loose packed (Tiberio 1988) may be thought to make the foot unstable, they may actually allow the foot to adapt to the surface, thus reducing the amount of postural sway up the kinetic chain. The wider base of support in the medial-lateral (ML) direction may lend itself to greater postural stability in that direction (Tsai, Yu et al. 2006). Furthermore, greater contact area with the standing surface may allow for greater cutaneous sensory feedback, which may aid in neuromuscular control of the postural muscles to achieve better balance performance (Hertel, Gay et al. 2002).

The present results did not support our hypothesis and demonstrated that the PRO group only had better balance performance than the NEU group in one of six TTB variables, (TTB mean minima in the ML direction). The other five TTB variables measuring balance performance were not different between foot type. As discussed above, there may have been a difference in the ML plane and not the AP plane due to pronated feet having a wider base of support in the ML direction than neutral feet. This seems to be the best explanation. However, if the reason for our seeing results between the PRO and NUE group were strictly due to the difference in foot width, we would expect to have seen a difference between the PRO and SUP groups also. This was not the case, so we must conclude that our results may be due to a combination of anatomical factors.

This result differs from previous findings on foot type and balance (Hertel, Gay et al. 2002; Tsai, Yu et al. 2006). Tsai et al. (2006) observed that individuals with pronated feet had poor postural control in the AP plane, but not ML. They speculated that subjects with pronated feet have better balance in the ML direction due to a wider base of support. Hertel et al. (2002) found no significant difference between pronated and neutral foot types, but found that subjects with pronated feet had better balance performance than those with supinated feet. Two other studies found no significant difference in balance performance between pronated and neutral feet (Olmsted 2004; Cote, Brunet et al. 2005). The difference in the results of these studies compared to our study may be because they used traditional COP values to assess balance performance, whereas we used TTB. This is significant because traditional COP excursions used in previous research do not take the border of the foot into account (Hertel and Olmsted-Kramer 2007). The wider base of support observed in pronated feet type may have resulted in larger COP excursions, simply due to the fact that it had more area in which to move than supinated or neutral feet. With the wider base of support, it is possible that the pronated group had increased COP sway area (poor balance), while achieving better TTB scores (good balance). Our study found that PRO group may actually have better balance performance than normal foot individuals in the ML plane. Previous research also speculated that (Hertel, Gay et al. 2002; Tsai, Yu et al. 2006) subjects with pronated feet may have better balance performance only in the ML plane due to a wider base of support, and also increased plantar cutaneous nerve input from increased ground contact. Clinically, a finding in the frontal plane is more meaningful because we know that ankle injuries occur in the frontal plane more commonly than in the sagittal plane with an inversion mechanism (Garrick 1977; Hertel 2002).

We also hypothesized that the SUP group would exhibit poorer balance than both PRO and NEU groups. We hypothesized this based on speculation that the SUP group may be at an anatomical disadvantage for balance performance due to the rigidity of the mid-tarsal joins not allowing for easy adaptation to ground surfaces, and also decreased cutaneous afferent input as a results of less medial foot contact with the ground surface (Hertel, Gay et al. 2002; Olmsted 2004; Cote, Brunet et al. 2005; Tsai, Yu et al. 2006). However, our results did not demonstrate that the SUP group had poor balance performance compared with NEU and PRO groups. This result is in agreement with findings from some studies (Olmsted 2004; Cote, Brunet et al. 2005), but is in disagreement with the other studies (Hertel, Gay et al. 2002; Tsai, Yu et al. 2006) which observed individuals with a supinated foot type to have poor balance performance compared to those with neutral or pronated feet. The difference in results may be due to the difference in measures used to assess balance performance and foot type (Hertel, Gay et al. 2002; Olmsted 2004; Cote, Brunet et al. 2005; Tsai, Yu et al. 2006).

We hypothesized that the PRO group would reach farther on the SEBT in all directions than the NEU and SUP groups due to a wider base of support allowing better balance (Olmsted 2004; Cote, Brunet et al. 2005). However, our results did not demonstrate that individuals in the PRO group had better balance performance than individuals in the SUP or NEU groups. We observed that the ability to reach maximally in three directions (anterior, posteromedial, and posterolateral) was not different among foot types. This result differs from previous research. Cote et al. (2005) found no significant difference in maximum reach in the PM direction between individuals with different foot type, but demonstrated that individuals with the SUP foot type demonstrate greater maximum reach than the NEU and PRO groups in the PL direction (Cote, Brunet et al. 2005). This is in agreement with findings reported by Olmsted et al. (2004) that SUP foot type have greater max reach in the posterolateral direction than other foot types while wearing orthotics. Cote et al. (2005) also reported that the PRO group demonstrated significantly greater max reach than the other foot types in the anterior direction While it is unclear why our study differs in these results, we may speculate that it could be because we included individuals with varying level of physical activity. Since chronic physical activity alters an individual's neuromuscular control, and increases muscular involvement during movement patterns (Carroll, Riek et al. 2001) we may speculate that those with decreased or no physical activity may perform more poorly on a dynamic balance task such as the SEBT, simply due to poor fitness. Variability also may be due to the number of trial re-takes a subject had to perform if they lost their balance or touched down. A greater number of trials may have led to greater practice for some subjects but not others. Lastly, we did not control for how fast subjects reached during the SEBT. Anecdotally we observed that some subjects reached much faster than others. They may have successfully completed the trial, but this may not mean that they actually had great balance because they performed the task so quickly.  However, more research is needed in this area to determine if these factors may confound the data. It is worth noting that we observed a statistically insignificant trend suggesting the SUP group may have greater maximum reach in the posterolateral direction (98.1 +/- 9.64) compared to NEU (92.1 +/- 12.6)  and PRO (92.7 +/- 13.8) groups. Lack of statistically significant difference may be attributed to low statistical power due to high variability in data.

We also assessed correlations between 1) FPI score and TTB minima, 2) FPI score and SEBT scores, and 3) TTB minima and SEBT score. The first two analysis (FPI score vs. TTB score and FPI score vs. SEBT) were conducted to see if there is a linear relationship between the degree of foot pronation/supination and balance performance. If such a relationship exists, clinicians can use FPI to identify individuals with poor balance performance. We hypothesized that individuals with greater foot pronation (higher FPI scores) would demonstrate higher TTB and SEBT max reach scores (positive correlation). However, we did not observe any clinically meaningful relationship between FPI and TTB minima or SEBT scores **(Table 5).**  Since we did not discover a relationship between FPI scores and balance performance, the FPI-6 may not be a useful tool for predicting balance performance as we had originally hypothesized.

The correlation between TTB and SEBT max reach score was assessed to see if both novel tests of dynamic balance performance are measuring the same dependent construct. Both tests are valid assessments of dynamic balance performance, and if they are measuring the same construct, the scores from 2 tests would be highly correlated. We hypothesized that 2 measures assess the same construct, and therefore individuals with higher TTB scores would also have higher SEBT maximum reach test scores. Contrary to our hypothesis, our results did not demonstrate any relationship between TTB and SEBT maximum reach test scores. The lack of relationship between the scores may be due to the fact that the two instruments are measuring a different type of dynamic balance performance. The SEBT is a measure of dynamic balance performance that is considered to be more functional than static stance tests (Cote, Brunet et al. 2005). Because the SEBT involves moving and bending at the knee (Hertel, Miller et al. 2000) it may be influenced by strength and neuromuscular control of the entire lower extremity. On the other hand, TTB is a novel assessment of balance performance used primarily in research. TTB testing does not involve bending at the knee like the SEBT, so it may influenced by knee and hip motion in addition to the ankle and foot. Further research in this area must be performed to determine exactly what each test measures, and why there is no relationship between scores. Although both TTB and SEBT measures are being increasingly used in the research and clinical settings (Wegen and Van Emmerik 2002; Olmsted 2004; Cote, Brunet et al. 2005; Haddad, Gagnon et al. 2006; Hertel, Olmsted-Kramer et al. 2006; Cain, Nicholson et al. 2007; Hertel and Olmsted-Kramer 2007; McKeon and Hertel 2007; McKeon and Hertel 2008; Hoch and McKeon 2011), no study has examined the correlation between the scores to see if they may be measuring the same construct (dynamic balance performance). Since no relationship exists between these scores, we may conclude that they both measure different aspects of balance performance. This is useful for future studies because it demonstrates the need to assess dynamic balance performance using multiple tools in order to determine the cause of any inability to perform well on balance tasks or sports.

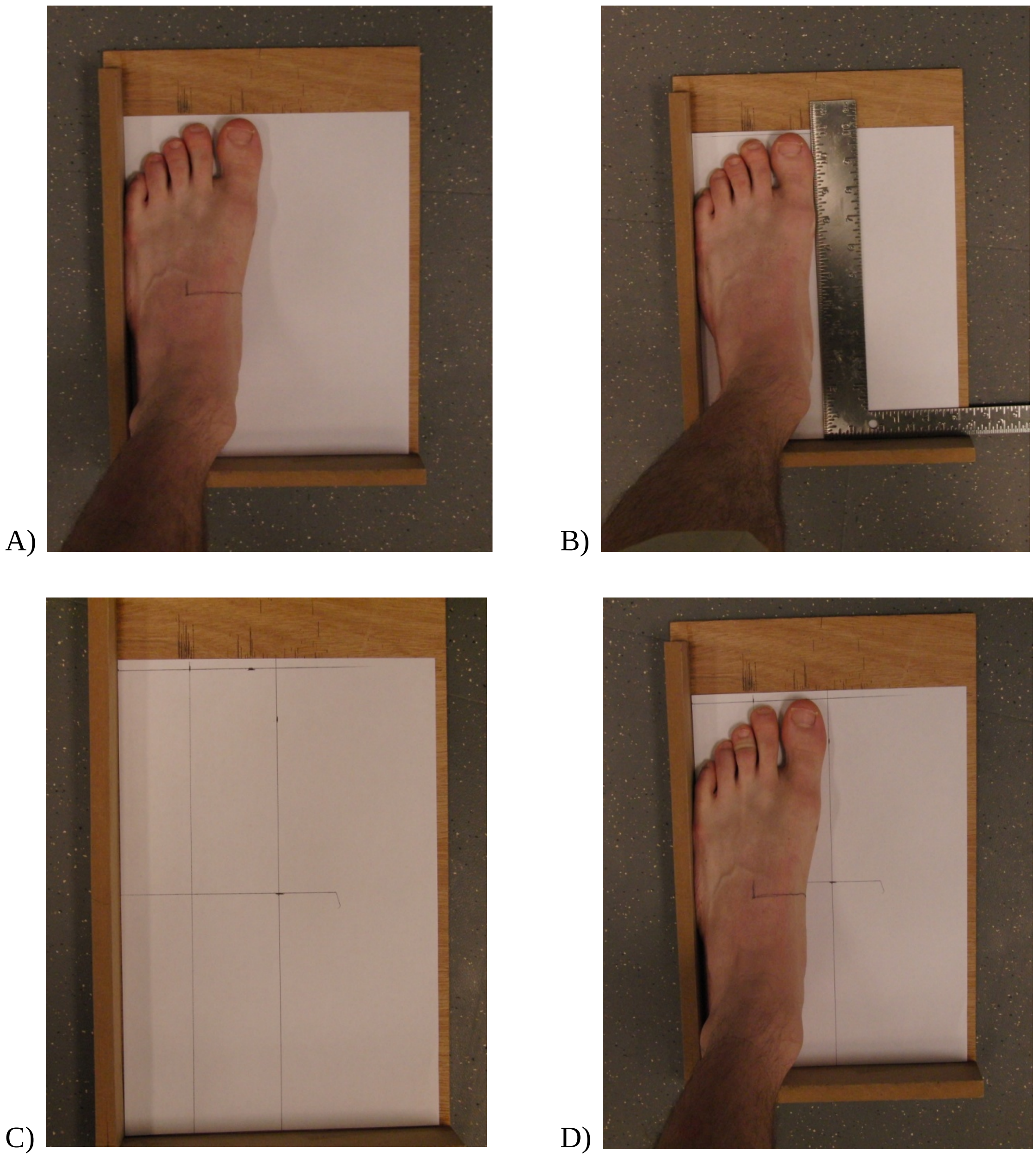
This study is not without limitations. We included individuals with varying levels of physical activity, which may have led to greater variability in scores on the balance performance tasks due to varying fitness levels. However, we did exclude individuals with injuries and experience in balance sports/training to exclude participants who may be influenced by factors known to affect balance performance. We did not exclude those who may have been fatigued from exercise prior to testing, which may have confounded the results because previous research has demonstrated that fatigue may impair postural control (Johnston, Howard et al. 1998). Lastly, the results of the study may have been more clinically applicable if balance tasks were performed while wearing shoes as well as in bare feet, since athletes are wearing shoes during most sporting events.

In future studies, it would be beneficial to exclude subjects based on the amount of physical activity they perform on a regularly basis, and if they had performed physical activity prior to testing. Future studies may also try to perform similar balance tasks in a variety of conditions (shod, unshod, wearing sleeve) to determine if balance performance is affected more by the sensory input, or mechanical rigidity of the foot. Also, it may be beneficial to determine how taping and bracing affects foot type and balance using the FPI-6 and TTB measures. This will help to determine if taping and bracing is detrimental or helpful specifically for balance performance in individuals with pronated and supinated feet.

In conclusion, this study demonstrated a significant difference between foot type and TTB balance performance in the medial-lateral direction, but no significant differences were found using any other measure. Furthermore, no correlations were found between TTB values/FPI-6 scores, FPI-6 scores/SEBT max reach, or TTB values/SEBT max reach. Our finding of no significant relationship between SEBT and TTB scores is clinically helpful, because it indicates that both validated, novel measures of dynamic balance performance may not be measuring the same thing. This may direct future research to determine what exactly is being measured by the TTB and SEBT tests. The results of our study indicate that the foot type may not have an effect on dynamic balance performance, except in the ML plane. Clinically this may aid in our knowledge and assessment of foot type in order to determine the underlying causal factors behind ankle and foot injuries. If the reasons for individuals with pronated feet having better balance only in the ML plane due to a wider base of support, then we may want to consider orthotic intervention for feet that have a narrow ML base of support. This may explain why previous research has demonstrated that orthotic intervention may be helpful for increasing balance performance in those with supinated feet and not pronated or neutral feet (Cote, Brunet et al. 2005). This knowledge may help to increase balance performance and perhaps reduce the number of ankle injuries that occur, since ankle injury is commonly associated with poor balance performance (Tropp, Ekstrand et al. 1984; Watson 1999; McGuine, Greene et al. 2000).

## FIGURES

**Figure 1.A-D :** Foot Boundary Measuring



A) B) C) D)

**Figure 2:** Time-To-Boundary Border (Hertel, Olmsted-Kramer et al. 2006)

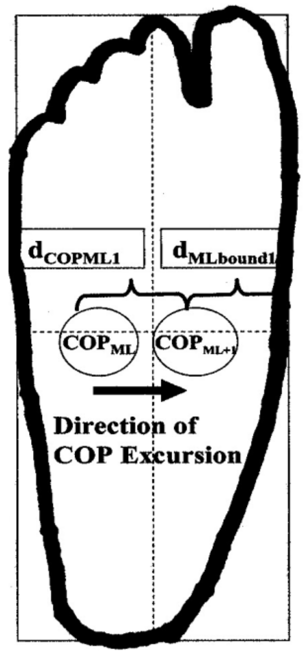


**Figure 3:** Time-To-Boundary Minina Time Series (Hertel, Olmsted-Kramer et al. 2006)

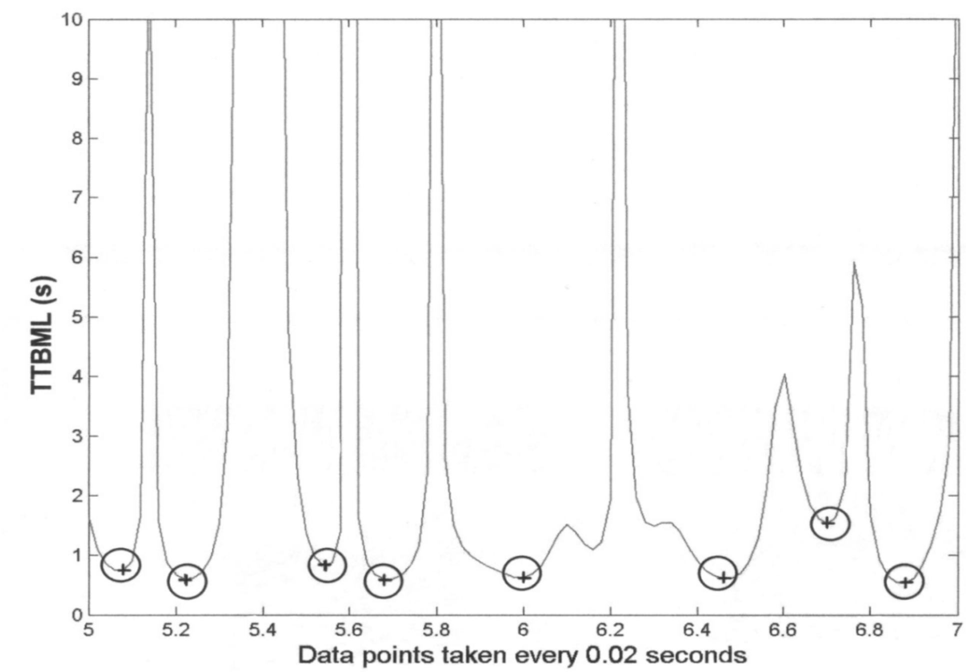


**Figure 4:** Star Excursion Balance Test  (Anterior, Posterolatera, Posteromedial)

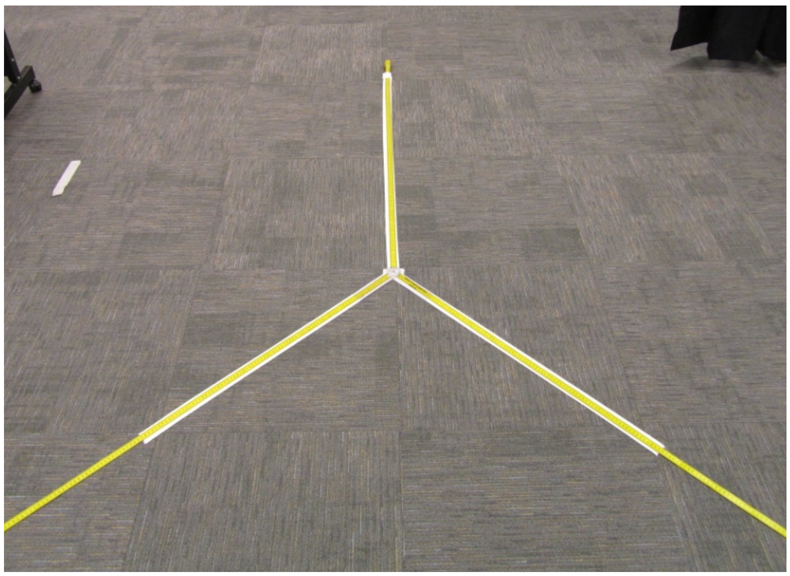


**Figure 5:** Time-To-Boundary Absolute Minima  (*Pro > Neu in medial-lateral TTB absolute minima)

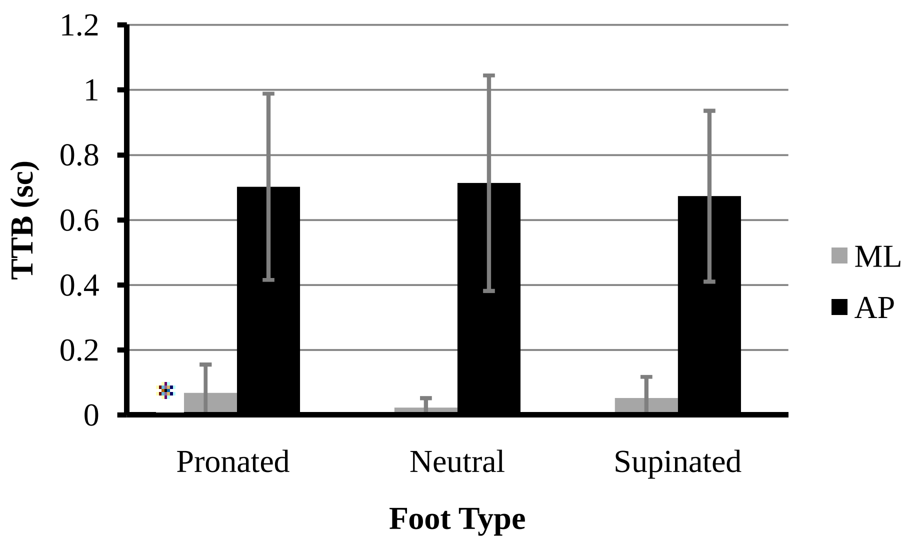



**Figure 6:** Time-To-Boundary Mean Minima

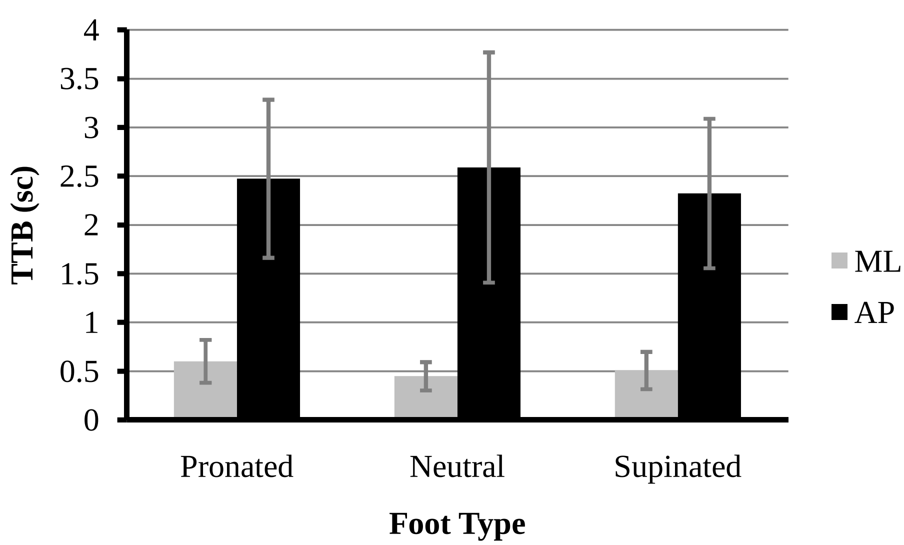


**Figure 7:** Time-To-Boundary Standard Deviation

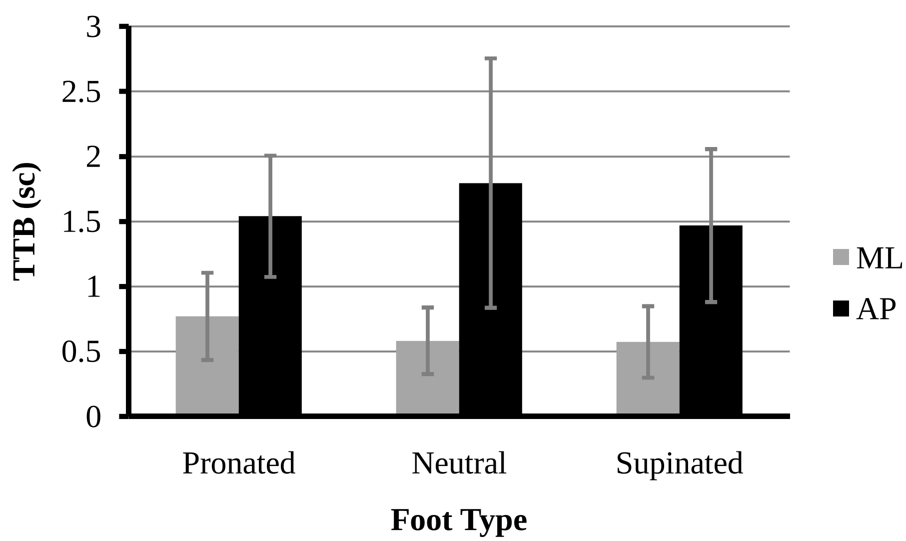
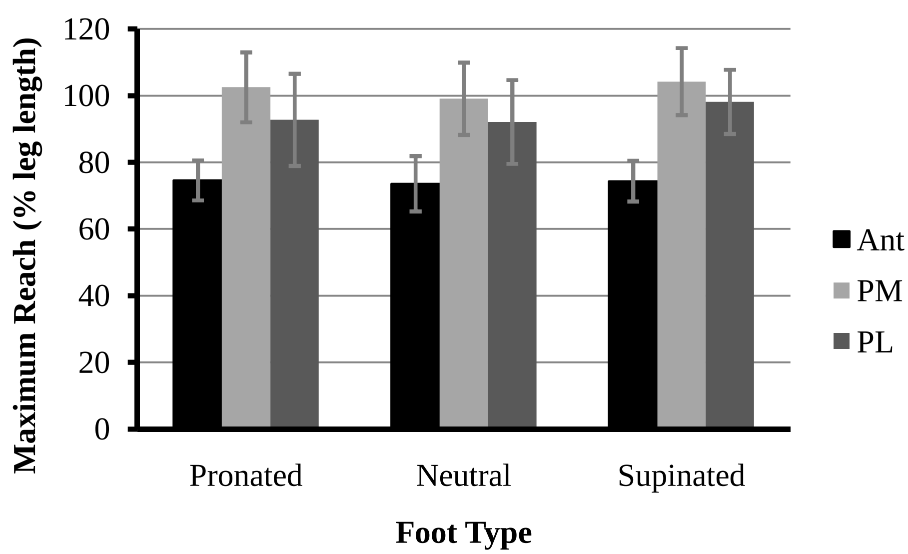



**Figure 8:** Star Excursion Maximum Reach Distance



## TABLES

**Table 1: Demographic Information**

| | N | Gender | | Weight (kg) | Height (cm) |
|---|---|---|---|---|---|
| | | Male | Female | | |
| Pronated | 20 | 11 | 9 | 75.3 ± 12.2 | 173.7 ± 10.4 |
| Neutral | 21 | 5 | 16 | 66.0 ± 13.0 | 169.3 ± 8.97 |
| Supinated | 20 | 11 | 9 | 68.8 ±17.5 | 173.9 ± 9.39 |
| Total | 61 | 27 | 34 | 69.6 ± 14.5 | 171.8 ± 9.65 |

**Table 2: Time-To-Boundary Mean and Standard Deviation Totals**

| | Pronated | | Neutral | | Supinated | |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD |
| Absolute Minima – ML (sec) | .068 | .088 | .023 | .029 | .053 | .065 |
| Absolute Minima – AP (sec) | .702 | .286 | .714 | .331 | .674 | .263 |
| Mean Minima – ML (sec) | .603 | .220 | .449 | .145 | .508 | .191 |
| Mean Minima – AP (sec) | 2.47 | .081 | 2.59 | 1.18 | 2.32 | .767 |
| SD Minima – ML (sec) | .770 | .335 | .583 | .256 | .573 | .275 |
| SD Minima – AP (sec) | 1.54 | .467 | 1.80 | .959 | 1.47 | .588 |

| Table 3: Star Excursion Balance Test Mean and Standard Deviation Totals | | | | | | |
|---|---|---|---|---|---|---|
| | **Pronated** | | **Neutral** | | **Supinated** | |
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| Posteromedial (% height) | 102.5 | 10.5 | 99.1 | 10.8 | 104.2 | 10.1 |
| Posterolateral (% height) | 92.7 | 13.8 | 92.1 | 12.6 | 98.1 | 9.64 |
| Anterior (% height) | 74.6 | 6.01 | 73.6 | 8.28 | 74.4 | 6.08 |

**Table 4: Kappa Measure of Agreement for Intrarater and Interrater FPI-6 Scores**

| | Talar Head | Malleolar Curves | Calcaneal Position | TNJ Bulge | Med. Long. Arch | Forefoot Position | Sum | Foot Category |
|---|---|---|---|---|---|---|---|---|
| Intrarater | .859 | .669 | .391 | .429 | 1 | .164 | .457 | **.636** |
| Interrater | .333 | .211 | 1.00 | .333 | .893 | .167 | .341 | **.800** |

**Table 5: Relationship Between Foot Posture Index Scores and TTB Minima Values**

| | ML Absolute Minima | | AP Absolute Minima | | ML Mean Minima | | AP Mean Minima | | ML SD Minima | | AP SD Minima | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **r** | **P** | **r** | **P** | **r** | **P** | **r** | **P** | **r** | **P** | **r** | **P** |
| FPI Score | .104 | .426 | -.020 | .880 | .187 | .150 | .014 | .916 | .266 | .038* | .010 | .939 |

TTB = Time-to-boundary / Ant = Anterior / PM = Posteromedial / PL = posterolateral / ML = Medial-lateral / AP = Anterior-posterior / SD = Standard Deviation / r = Pearson's R / P = P-value / * = significant relationship

**Table 6: Relationship Between Foot Posture Index Scores and SEBT Max Reach Scores**

| | Pearson's r | P Value |
|---|---|---|
| SEBT Ant | 0.002 | 0.987 |
| SEBT PM | -0.096 | 0.461 |
| SEBT PL | -0.211 | 0.103 |

SEBT = Star Excursion Balance Test  Ant = Anterior  PM = Posteromedial  PL = Posterolateral

**Table 7: Relationship Between Star Excursion Balance Test (SEBT) scores and TTB Minima Values**

| | ML Absolute Minima | | AP Absolute Minima | | ML Mean Minima | | AP Mean Minima | | ML SD Minima | | AP SD Minima | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **r** | **P** | **r** | **P** | **r** | **P** | **r** | **P** | **r** | **P** | **r** | **P** |
| SEBT Ant | -.232 | .072 | .169 | .194 | -.147 | .259 | -.133 | .307 | -.128 | .325 | -.124 | .342 |
| SEBT PM | .074 | .572 | .057 | .665 | .089 | .495 | .052 | .688 | .107 | .410 | .039 | .767 |
| SEBT PL | -.090 | .491 | .053 | .687 | .088 | .499 | .094 | .471 | .037 | .774 | .072 | .583 |

TTB = Time-to-boundary / Ant = Anterior / PM = Posteromedial / PL = posterolateral / ML = Medial-lateral / AP = Anterior-posterior / SD = Standard Deviation / r = Pearson's R / P = P-value

## APPENDICES

### APPENDIX 1: FOOT POSTURE INDEX

# *THE FOOT POSTURE INDEX©*
# *FPI-6*

**Reference Sheet**

The patient should stand in their relaxed stance position with double limb support. The patient should be instructed to stand still, with their arms by the side and looking straight ahead. It may be helpful to ask the patient to take several steps, marching on the spot, prior to settling into a comfortable stance position. During the assessment, it is important to ensure that the patient does not swivel to try to see what is happening for themself, as this will significantly affect the foot posture. The patient will need to stand still for approximately two minutes in total in order for the assessment to be conducted. The assessor needs to be able to move around the patient during the assessment and to have uninterrupted access to the posterior aspect of the leg and foot.

If an observation cannot be made (e.g. because of soft tissue swelling) simply miss it out and indicate on the datasheet that the item was not scored.

If there is genuine doubt about how high or low to score an item always use the more conservative score.

| **Rearfoot Score** | **-2** | **-1** | **0** | **1** | **2** |
|---|---|---|---|---|---|
| Talar head palpation | Talar head palpable on lateral side/but not on medial side | Talar head palpable on lateral side/slightly palpable on medial side | Talar head equally palpable on lateral and medial side | Talar head slightly palpable on lateral side/ palpable on medial side | Talar head not palpable on lateral side/ but palpable on medial side |
| Curves above and below the malleoli | Curve below the malleolus either straight or convex | Curve below the malleolus concave, but flatter/ more shallow than the curve above the malleolus | Both infra and supra malleolar curves roughly equal | Curve below malleolus more concave than curve above malleolus | Curve below malleolus markedly more concave than curve above malleolus |
| Calcaneal inversion/eversion | More than an estimated 5° inverted (varus) | Between vertical and an estimated 5° inverted (varus) | Vertical | Between vertical and an estimated 5° everted (valgus) | More than an estimated 5° everted (valgus) |
| **Forefoot Score** | **-2** | **-1** | **0** | **1** | **2** |
| Talo-navicular congruence | Area of TNJ markedly concave | Area of TNJ slightly, but definitely concave | Area of TNJ flat | Area of TNJ bulging slightly | Area of TNJ bulging markedly |
| Medial arch height | Arch high and acutely angled towards the posterior end of the medial arch | Arch moderately high and slightly acute posteriorly | Arch height normal and concentrically curved | Arch lowered with some flattening in the central portion | Arch very low with severe flattening in the central portion – arch making ground contact |
| Forefoot abd/adduction | No lateral toes visible. Medial toes clearly visible | Medial toes clearly more visible than lateral | Medial and lateral toes equally visible | Lateral toes clearly more visible than medial | No medial toes visible. Lateral toes clearly visible |

*For further information, manuals and extra datasheets see: www.leeds.ac.uk/medicine/FASTER/FPI/*

## *Foot Posture Index Datasheet*

| ***Patient name*** | ***ID number*** |
|---|---|
| | |

| | *FACTOR* | *PLANE* | SCORE 1<br>Date______________<br>Comment__________ | | SCORE 2<br>Date______________<br>Comment__________ | | SCORE 3<br>Date______________<br>Comment__________ | |
|---|---|---|---|---|---|---|---|---|
| | | | ***Left***<br>*-2 to +2* | ***Right***<br>*-2 to +2* | ***Left***<br>*-2 to +2* | ***Right***<br>*-2 to +2* | ***Left***<br>*-2 to +2* | ***Right***<br>*-2 to +2* |
| **Rearfoot** | Talar head palpation | *Transverse* | | | | | | |
| | Curves above and below the lateral malleolus | *Frontal/ transverse* | | | | | | |
| | Inversion/eversion of the calcaneus | *Frontal* | | | | | | |
| **Forefoot** | Prominence in the region of the TNJ | *Transverse* | | | | | | |
| | Congruence of the medial longitudinal arch | *Sagittal* | | | | | | |
| | Abd/adduction forefoot on rearfoot | *Transverse* | | | | | | |
| | **TOTAL** | | | | | | | |

**Reference values**
*Normal = 0 to +5*
*Pronated = +6 to +9, Highly pronated 10+*
*Supinated = -1 to -4, Highly supinated -5 to -12*

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