Impact of foot type, quadriceps angle, and minimalist footwear on static postural stability

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A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Kinesiology
in the Department of Kinesiology

Mississippi State, Mississippi

August 2019
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**Background:** In years 2011-2014, 8.6 million sports-related injuries were reported each year and falls have been identified as a main cause. **Purpose:** To determine the impact of foot type, quadriceps angle, and Vibram™ footwear on postural stability. **Methods:** Twenty-four males (age 21.38±2.50yr; height 1.74±0.06m; mass 71.24±10.37kg) were categorized as pronated, supinated, and neutral feet using FPI and bilateral quadriceps angles were measured. Participants were tested on barefoot, Vibram™ Bikila and Vibram™ Trek (VT), on stable/unstable, bilateral/unilateral, eyes open/closed conditions. Sway variables were analyzed using 3(foot type) × 3(footwear) repeated measures ANOVA. Pearson product correlation was performed for quadriceps angle with sway variables. **Results:** Footwear main effect significance was evident in all conditions except stable unilateral eyes open condition, with lower values for barefoot followed by VT. **Conclusion:** Static balance in BF is superior to shod conditions in all situations except the extremely challenging condition, in which VT showed greater balance.
DEDICATION

I dedicate this work to my father who always saw my potential before I did. He was a person who did not tell me how to live, but who set an amazing example of how to live.
ACKNOWLEDGEMENTS

I would like to extend my sincere gratitude to my major professor Dr. Adam Knight and my co-major professor Dr. Harish Chander for their continuous guidance and encouragement. They never hesitated to support me anytime despite their very busy schedules. Thank you very much for driving me on the right path to achieve the highest standards, for believing in me and having patience with me.

Also, I am very grateful to Dr. Chih-Chia (J.J.) Chen and Dr. Zhujun Pan who serve as my committee members. Also, I should mention all the faculty members who taught me and heightened my interest in research and all the staff members who helped me directly or indirectly in various ways during my graduate student life.

I must express my thanks to all my labmates including Alana Turner who helps me with everything. Thank you very much, everyone, for sharing knowledge with me and for everything you do.

I would like to acknowledge Ms. Diane Daniels, Director in Developmental Programs, who is the best supervisor anyone could ask. Thank you very much for putting my schoolwork ahead of anything at work, for releasing me anytime I requested.

A huge thank should go to my husband Don, who is the reason for I am here today, the optimistic man encouraging me all the time while being my ‘forever guinea pig’ without complaining. Thank you very much for tolerating all my forgetfulness and all the irrelevant stories I rant every day.
Finally, a big thank goes to my participants who helped me to make this project a success.
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OPERATIONAL DEFINITIONS

• Posture: Orientation of the body segments in the space (D A Winter, 1995)
• Balance: Dynamics of the body alignment in order to prevent falling (D A Winter, 1995)
• Center of mass (COM): The point where entire body mass is uniformly balanced in three-dimensional space (D A Winter, 1995)
• Center of gravity (COG): The vertical extension of the center of mass (D A Winter, 1995)
• Centre of pressure (COP): The point where the average of total pressures acting on the surface of the body which is in contact with the ground (D A Winter, 1995)
• Postural stability: Ability to maintain a stable COM during perturbations (Fay B Horak, 2006)
• Postural orientation: Ability of active maintenance of body tone and proper relationship among body segments with regard to gravity and the surrounding environment (Fay B Horak, 2006)
• Postural control: Capability to maintain postural stability and orientation (Fay B Horak, 2006) which is achieved via maintaining the body's COM within the BOS (F B Horak, 1987).
LIST OF ABBREVIATIONS

COM - Center Of Mass
COG – Center Of Gravity
COP- Center Of Pressure
BOS - Base Of Support
MLA - Medial Longitudinal Arch
AHIMS- Arch Height Index Measurement System
AHI- Arch Height Index
FPI- Foot Posture Index
Q angle - Quadriceps angle
VFF - Vibram™ Five Fingers Footwear
BF- Barefoot condition
VB- Vibram™ Bikila Footwear
VT- Vibram™ Trek Ascent Footwear
BL- Bilateral stance
UL- Unilateral stance
EO-Eyes opened condition
EC- Eyes closed condition
N- Neutral foot type
S- Supinated foot type
P- Pronated foot type
CHAPTER I
INTRODUCTION

In the years of 2011-2014, an average of 8.6 million sports and recreation-related injuries were reported each year. Among these, falls have been identified as the most common mechanism of injury which was attributed to 27.9% of all injuries. 65% of these injuries were reported in the age group of 5-24 years and 61% were reported in males. The occurrence of lower extremity injuries was 42% (Yahtyng S, Li-Hui, 2016). Therefore, it is apparent that fall-related injuries are extremely common during sports and recreation. Similar to any other instance, postural instability could act as one of the major causative factors of injuries in sports and recreation (McGuine & Keene, 2006; Muehlbauer, Gollhofer, & Granacher, 2015; Sanders et al., 2017). In addition to increasing the susceptibility to injuries, poor postural stability could lead to poor performance outcomes in sports (Hrysomallis, 2011).

Postural stability can be defined as the ability to manage the center of mass (COM) within the base of support (BOS), and balance can be described as the ability to maintain the center of gravity (COG) within the BOS (F B Horak, 1987; Fay B Horak, 2006). The postural control system is responsible for maintaining proper stability, which will be discussed later in chapter II. Although the words "postural stability" and "balance" are frequently used interchangeably in the realm of biomechanics, balance is a measurement which can be used to quantify and assess postural stability. Postural stability is mainly categorized in two ways as static balance (maintainance of motionless upright unipedal or bipedal stance) and dynamic balance (maintain
Among these, maintaining dynamic balance is considered more challenging and requires more complex control than static balance (Fay B Horak, 2006). Factors affecting postural stability are mainly divided into two major categories, intrinsic (human) factors and extrinsic (environmental) factors. Nature of the contact surface, surface area of the contact surface, surface friction (coefficient of friction), presence of contaminants on the surface (water, sand, oil), footwear, nature of the task, workload and environmental conditions (light, rain, mist, fog) can be considered as extrinsic factors (H Chander, Wade, Garner, & Knight, 2017; Harish Chander, Morris, Wilson, Garner, & Wade, 2016; DeBusk, Hill, Chander, Knight, & Babski-Reeves, 2018; Fay B Horak, 2006). Age, general health, physical fitness, body weight, structural orientation of the lower extremity, injuries, pathologies, eyesight, fatigue, attention level, position of the body, lack of sleep, past experience, and anticipation are considered as intrinsic factors (Antwi-Afari et al., 2017; Gauchard, Jeandel, Tessier, & Perrin, 1999; Fay B Horak, 2006; Kodithuwakku Arachchige, Chander, & Knight, 2019). Deterioration of these factors can negatively impact balance by increasing the amount of postural sway which may eventually trigger a fall (D. Lin, Seol, Nussbaum, & Madigan, 2008).

The human foot is specifically built for weight bearing and for maintaining postural stability. These functions primarily depend on the shape of the foot (Razeghi & Batt, 2002). A number of small bones form the arch of the foot, which aids in stability, weight distribution, flexibility, gait, and shock absorption (Fukano & Fukubayashi, 2009; Jung, Koh, & Kwon, 2011). There are various classification methods that are used to classify the foot type. Direct visual inspection, inspection of footprints/photographs, anthropometric measurements, and radiological methods are such popular methods (Cavanagh et al., 1997; Kodithuwakku Arachchige et al., 2019;
Although there is no universally accepted method to classify feet (Kodithuwakku Arachchige et al., 2019; Razeghi & Batt, 2002), there are some favored methods of classification which are being widely used. One method is the foot posture index (FPI) which classifies feet into supinated, pronated and neutral categories. This is a simple method which an investigator assesses the individual’s feet by inspection and palpation. Although this is a subjective measurement, it has been proven to have good inter-rater reliability (Morrison & Ferrari, 2009). In the studies which were done on the effect of foot type on balance, both pronated and supinated foot types were found to affect static and dynamic balance (Carvalho et al., 2015). Another popular method of classifying feet is according to the medial longitudinal arch (MLA) height, which is the main arch of the foot that has a remarkable role in foot function (Chang, Hung, Wu, Chiu, & Hsu, 2010). According to the MLA height, foot types have been identified as high arch (pes cavus), average arch (rectus foot) and flat arch (pes planus) (Tong & Kong, 2013). The impact of MLA height on balance has been widely studied and is found to affect balance (Tsai, Yu, Mercer, & Gross, 2006). Arch height index (AHI) is also been used for foot classification in balance studies (Cobb, Bazett-Jones, Joshi, Earl-Boehm, & James, 2014).

Additionally, quadriceps angle (Q angle) is another significant component of the lower extremity that can affect balance. Q angle is the angle between the quadriceps load vector and the patellar tendon load vector (Mizuno et al., 2001). It is graphically defined as the acute angle between two imaginary lines with knee joint in full extension; the first line is drawn between the center of the patella and the tibial tubercle, and the second line is drawn between the center of the patella and the anterior superior iliac spine (Figure 1). Anatomical variations of the Q angle have also been
reported to impact the postural stability (Horton & Hall, 1989; Meira Mainenti, de Carvalho Rodrigues, Mendes de Sousa, Ribeiro da Silva, & de Sá Ferreira, 2014; Mizuno et al., 2001). However, the studies which were done on the Q angle have predominantly focused on knee disorders such as patellar instability and patellofemoral pain syndrome (Citaker et al., 2011). The number of studies done on the effect of Q angle on postural stability in healthy population is minimal.

![Quadriceps angle](Floyd, 2009)

Footwear acts as the medium between human body and standing surface (Harish Chander, Garner, & Wade, 2014), hence it can be considered as a decisive extrinsic factor influencing postural stability. The effects of footwear on balance are found to be altered by the type of
footwear (Harish Chander et al., 2016), weight (Harish Chander et al., 2014), material (Garner, Wade, Garten, Chander, & Acevedo, 2013), heel height, heel type, midsole hardness (Robbins, Waked, Gouw, & McClaran, 1994), midsole thickness (Menant, Steele, Menz, Munro, & Lord, 2008; Robbins et al., 1994) and shaft height (Cikajlo & Matjačić, 2007; Stefanyszyn & Nigg, 2000).

Although the ability to maintain postural stability is considered to be best in the barefoot condition (Alghadir, Zafar, & Anwer, 2018; Shinohara & Gribble, 2019; D A Winter, 1995), some investigators have shown minimalist footwear such as Vibram™ Five Fingers footwear (VFF) elicit better static balance than barefoot (B. S. Smith et al., 2015). However, due to the limitations of previous studies done on VFF, most of its effects and properties still remain unclear. Specifically, the distinct features of different VFF types and balance are yet to be investigated.

Therefore, the purpose of this study was to investigate the impact of foot type, Q angle, and two types of Vibram™ five fingers footwear on static postural stability in healthy, recreationally active, college-aged males.
HYPOTHESES

Foot type hypothesis
Specific aim 1
To investigate the effect of foot type on static balance
H01: There will be no significant difference in static balance between different foot types
HA1: There will be a significant difference in static balance among participants with pronated and supinated foot types when compared to the participants with neutral foot type

Quadriceps angle hypothesis
Specific aim 2
To investigate the impact of Q angle on static balance
H02: There will be no significant impact of Q angle on static balance
HA2: There will be a significant impact of Q angle on static balance

Specific aim 3
To investigate the correlation between Q angle and AHI/MLA height
H03: There will be no significant correlation between Q angle and AHI/MLA height
HA3: There will be a significant correlation between Q angle and AHI/MLA height

Footwear hypothesis
Specific aim 4
To investigate the effects of footwear on balance
H04: There will be no significant difference in static balance between barefoot condition and other two footwear conditions
HA4: There will be a significant difference in static balance between barefoot condition and other two footwear conditions
Specific aim 5

To investigate the effects of two types of Vibram™ five fingers footwear (Vibram™ Bikila and Vibram™ Trek Ascent) on static balance

H05: There will be no significant difference in participants’ static balance when exposed to the two types of footwear

HA5: There will be a significant difference in participants’ static balance when exposed to the two types of footwear
CHAPTER II
LITERATURE REVIEW

The purpose of this chapter is to analyze and condense the previous literature related to postural stability, different foot types, Q angle, and Vibram™ footwear. This chapter will be divided into seven sections. The first section will explain the basic concepts in postural control. The next five sections will include individual descriptions of foot types and its effect on postural stability, Q angle and its effect on postural stability, effect of foot type on Q angle, footwear and its effect on postural stability, footwear and its effect on postural stability and Vibram™ footwear and its effect on postural stability. The chapter will end with an overall conclusion of the previous literature.

**Postural stability**

Due to the imbalance of structure distribution within the body, maintaining postural stability has always been a constant challenge for humans. Postural stability is mainly achieved through the combination of detecting sensations by the afferent systems, integration at the higher centers and executing a motor plan via efferent systems (F B Horak, 1987; Fay B Horak, 2006; Shumway-Cook & Horak, 1986).

In order to detect intrinsic and extrinsic inputs, humans possess three sensory/feedback systems which are the visual system, vestibular system, and somatosensory system (Shumway-Cook & Horak, 1986). The visual system is comprised of the eyes, optic nerves, and optical tracts. It provides information regarding body position in the environment, alterations in the adjacent
environment as well as aid in maneuvering through obstacles (D A Winter, 1995). Since the visual system has the capability to detect changes faster than the other two systems, it enables us to react to sudden perturbations. Over time, many studies have been conducted to identify the role and importance of the visual system in maintaining balance. These studies were conducted on different types of populations across various age categories. It was found that postural sway increases in the eyes closed condition (Cernacek, Jagr, Harman, & Vyskocil, 1973; Nies & L Sinnott, 1991; Schmuckler & Tang, 2019), confirming the importance of visual feedback.

Muscle spindles, Golgi tendon organs, and cutaneous nerve receptors are collectively known as the somatosensory system. This system is responsible for detecting the relative position and movement of the body parts, called proprioception (D A Winter, 1995). Similar to the visual system, scientists have vastly studied the importance of the somatosensory system in maintaining balance. Dickin et al. (2012) have used whole body vibration (WBV) to create an alteration to the somatosensory system in 12 participants and their postural sway frequency and complexity were assessed before, immediately after, 10 minutes after, and 20 minutes after the WBV. It was found that their postural sway frequency and complexity were affected after the WBV.

The vestibular system is located in the inner ear and is responsible for detecting linear and angular accelerations of the head, gaze maintenance during head movements, head and trunk positioning, and slow body sway stabilization (Angelaki & Cullen, 2008; D A Winter, 1995). Although this is the slowest system among the three afferent systems, it acts as a reference during erroneous or confusing visual inputs. Horak (2010) did a review on the importance of the vestibular system in postural control and concluded that it has a crucial role in maintaining balance especially on unstable surfaces and with rapid body movements.
Although all three sensory systems provide information to the higher centers, the central nervous system (CNS) carries the ability of choosing required information at a given time, which is called the sensory organization (Dickstein, Peterka, & Horak, 2003; F B Horak & Hlavacka, 2001; Peterka, 2002). In addition, when there is a compromise to one of these afferent systems, the unaffected systems will compensate for the loss (Fay B Horak, 2010). For example, in the eyes closed situation or in a visual-referenced situation, the postural stability will be primarily maintained by the vestibular and somatosensory systems (Fukuoka, Nagata, Ishida, & Minamitani, 2001; F B Horak & Hlavacka, 2001; Peterka, 2002).

After the integration of afferent information carried to the CNS, the present body position is determined and the required output is programmed through the complex communication between the frontal cortex, motor cortex, cerebellum, basal ganglia, brain stem and spinal cord (Jacobs & Horak, 2007). This motor plan will be transmitted via the efferent circuits to be executed by the musculoskeletal system (F B Horak, 1987). The spinal cord, lower motor neurons, limb and trunk muscles play a major role in the execution. Alteration to any of these components within this multifactorial system will affect postural stability. This will manifest as an increase in postural sway, which will lead to loss of balance (D. Lin et al., 2008; Taube et al., 2006).

As mentioned before, maintaining balance is considered as the ability to sustain the COM within the BOS. Therefore, the BOS has remarkable importance in postural control. In quiet bilateral standing, individual’s BOS will be the area between their bilateral feet. In quiet unilateral standing, it will be the surface area of standing foot. During walking or running, the individual will have a dynamic BOS according to the position of the feet at a given time. Certainly, balance is directly related to the area of BOS. Therefore, it will be easier to maintain balance in bilateral stance than in unilateral stance due to larger BOS, giving more expanse for the COM to move (F
Many biomechanists have shown interest in testing this hypothesis by comparing balance in bilateral and unilateral stances. Matsuda et al. (2010) have assessed the postural sway parameters in 50 healthy soccer players in one-legged and two-legged conditions. Unilateral stance was assessed in the dominant leg and in the non-dominant leg. They have found that the balance is impaired in the unilateral stance due to the smaller BOS. However, there was no difference in balance found among the dominant and non-dominant legs (Matsuda, Demura, & Demura, 2010).

Apart from BOS, the nature of the standing surface plays a significant role in postural stability. In a situation in which BOS has not changed (eg: quiet bilateral stance), balance is found to be deteriorated on the unstable surface (Antwi-Afari et al., 2017). Usually, in balance studies, to induce a perturbation to the somatosensory system a foam pad will be placed on the force plate (Fay B Horak, Henry, & Shumway-Cook, 1997). The unstable surface (foam pad) will provide disorganized feedback to the somatosensory system and will cause the use of ankle strategy more challenging.
Figure 2. Inverted pendulum model. During the ankle strategy, body sways in the anteroposterior direction at the ankles as an inverted pendulum. White dot represents the COM, white vertical line represents the projection of COM (Fay B Horak, 2006).

There are two fixed-support synergies and two change-of-support synergies were introduced in postural control. Those were categorized according to the presence or absence of BOS change, hence ankle and hip strategies are classified as fixed-support synergies and stepping and grasping strategies are categorized as change-of-support synergies (Fay B Horak, 2006). During the ankle strategy, the body sways in the anteroposterior direction at the ankles as an inverted pendulum within the cone of stability (Figure 2). The ankle strategy is mainly applicable for minor perturbations (Fay B Horak, 2006). In a situation where the perturbation is moderately large and when the person is standing on a narrow BOS, the body elicits the hip strategy. In this strategy, there will be a lowering of body COM in order to maintain the balance. Following a larger perturbation where the person can no longer keep their COM within the BOS, the stepping
strategy occurs. In this strategy, the affected person will take a step forward which increases the BOS area and lowers the COM to counteract the instability. Grasping strategy is simply holding onto a nearby object in order to increase the BOS to maintain balance (Figure 3)(F B Horak, 1987; Fay B Horak, 2006; McIlroy & Maki, 1996).

![Figure 3. Quiet standing, ankle strategy, and hip strategy (D A Winter, 1995)](image)

There are different methods of balance analysis in the field of biomechanics such as subjective balance scoring systems, star excursion balance test, force platform (force plate), stabilometer, and Neurocom™ balance system (Harish Chander & Dabbs, 2016). Among these, the force plate is widely used in laboratory settings due to feasibility and affordability. It records the individual’s COP trajectory during a period of time (F B Horak, 1987) and can be used to quantify postural stability using postural sway variables such as COP displacement in anteroposterior and mediolateral directions, individual’s average displacement in anteroposterior.
and mediolateral directions, sway velocity, sway area, and other variables related to postural sway. Higher values for the postural sway variables represent a greater decrement in balance.

**Foot types and its effect on postural stability**

Creating the BOS during standing, human feet have a very important role in maintaining postural stability and have drawn researchers’ attention. Many researchers have shown that the abnormal foot types are associated with decreased static and dynamic postural stability (Cobb et al., 2014; Hertel, Gay, & Denegar, 2002; Tsai et al., 2006). As mentioned before, different researchers have implemented different methods to classify feet, such as the FPI, MLA height and AHI (Cobb et al., 2014; Flor, 2002; Tsai et al., 2006).

Dr. A. Redmond has introduced the FPI in 2001 in order to assess the foot type promptly in a quantitative manner considering the foot posture in frontal, sagittal and transverse planes during quiet standing (A. C. Redmond, Crosbie, & Ouvrier, 2006). Due to convenience, simplicity and needless of any instruments, this is being widely used in the clinical settings as well as in the laboratory settings. The classical FPI includes eight criteria and a modified version of FPI has been introduced with six criteria (FPI-6) following the elimination of Helbing’s sign and lateral border of the foot congruence due to poor reliability (A. C. Redmond et al., 2006). The modified version includes; talar head palpation, supra and infra lateral malleoli curvature inspection, calcaneal frontal plane position inspection, talonavicular joint prominence inspection, congruence of MLA inspection, abduction/adduction of forefoot on rearfoot inspection (A. C. Redmond et al., 2006) (Appendix A). Depending on the degree of the interested criterion, a score from -2 to +2 is given (Appendix A). While the participant is standing, the right and left legs will be observed separately and the total score of six criteria is taken (Figure 4). A total score of ≤+1 is classified as supinated, a score between >+1 to +7< is classified as neutral and a
A score of $\geq 7$ is classified as pronated feet (Buldt et al., 2015; A. C. Redmond, Crane, & Menz, 2008).

![Table: Foot Posture Index (6-item) Datashet]

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>PLANE</th>
<th>SCORE 1</th>
<th></th>
<th>SCORE 2</th>
<th></th>
<th>SCORE 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Date</td>
<td></td>
<td>Comment</td>
<td>Date</td>
<td></td>
<td>Comment</td>
<td>Date</td>
</tr>
<tr>
<td>Talor head palpitation</td>
<td>Front</td>
<td>Left $\geq 3$</td>
<td>Right $\geq 3$</td>
<td>Left $\geq 3$</td>
<td>Right $\geq 3$</td>
<td>Left $\geq 3$</td>
<td>Right $\geq 3$</td>
</tr>
<tr>
<td>Curves above and below lateral malleolus</td>
<td>Front</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inversion/erosion of the calcaneus</td>
<td>Front</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulge in the region of the TRU</td>
<td>Front</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Congruence of the medial longitudinal arch</td>
<td>Sagittal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abduction/adduction of the toes on the rear foot (too many toes)</td>
<td>Neutral</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 4.* Foot posture index-6 data collection sheet (A. C. Redmond et al., 2006)

FPI has been found to be influenced by age and pathologies such as musculoskeletal diseases and neurological diseases, but it does not affect by the body mass index (BMI) or gender (A. C. Redmond et al., 2008). It has been reported to have good inter-rater reliability and validity. Morrison and Ferrari. (2009) have conducted an assessment of 30 participants’ feet (ages 5-16yr) by two podiatrists with more than five years of experience. Both raters were trained on FPI-6 equally before the study and have assessed the FPI individually (Morrison & Ferrari, 2009). They have concluded that the FPI-6 has almost perfect reliability among the two raters. Cornwall et al. (2008) performed an analysis of 46 individuals’ bilateral feet using FPI by three observers (first year physical therapy student with no clinical experience, physical therapist with nine-years...
experience in general orthopedics and a physical therapist with more than 30 years of experience in foot and ankle orthopedics with previous experience in FPI assessment). They reported that there is good intra-rater reliability in assessing FPI but there is a learning effect during first 20 feet observation. Therefore, they have recommended training of at least 20 feet to minimize within-rater differences. However, they were not satisfied with their results on inter-rater reliability and concluded that FPI should be used and interpreted with extreme caution, especially in research (Cornwall, Mcpoil, Lebec, Vicenzino, & Wilson, 2008). Another group found that the FPI has moderate reliability but possibly could be ambiguous limiting its use in research (Evans, Copper, Scharfbillig, Scutter, & Williams, 2003). Due to these constraints, many researchers use more than one method of foot classification methods in their studies such as MLA height, navicular height, footprint or arch height index (AHI) in addition to the FPI (Cobb et al., 2014).

The ability to maintain postural stability in individuals with different foot types has been studied widely, however, the results are contradicting. Tsai et al. (2006) studied three groups of 15 individuals with neutral, pronated and supinated feet. Their unilateral balance on a firm surface and on foam were assessed using a force plate. They found that individuals with pronated and supinated feet have higher deterioration in balance than the individuals with neutral feet (Tsai et al., 2006). Similarly, after studying 111 undergraduate students’ FPI and balance, another group concluded that abnormal FPI can cause poor balance and thus could predispose to injuries and falls (Babayigit Irez, 2014). Heggannavar et al. (2016) assessed static balance of 30 adults categorized according to the FPI and found no impact of FPI on static balance (Heggannavar, Ramannavar, & Metgud, 2016). Correspondingly, Said et al. (2015) performed a study on 44 healthy, elderly individuals categorized into supinated, pronated and neutral feet to assess the
correlation between balance and FPI. They have found no correlation between FPI and balance (Mohd Said, Manaf, Bukry, & Justine, 2015). Furthermore, some studies have reported a deterioration of unilateral balance with pronated feet (Angin, İlçin, Subasi, & Simşek, 2013), some have shown a better balance with pronated feet than with neutral feet (Bonser, 2012). In addition, abnormal foot types are found to be associated with a greater number of foot/ankle injuries (Cain, Nicholson, Adams, & Burns, 2007). However, following a systematic review of nine studies on lower extremity injuries, Onate et al. (2016) concluded that due to the smaller sample size and the methods of foot posture analysis, foot type does not always show a significant association with injuries (Onate et al., 2016).

Using different measuring methods, MLA height has been widely used to assess the anatomy of the feet which categorizes the feet into normal (pes rectus), high (pes cavus) and low arched (pes planus) feet. Among these methods of measuring MLA height, the arch height index measurement system (AHIMS) is a novel device which is used to measure MLA height. In addition, AHIMS can be used to measure foot length, truncated foot length, and to calculate arch height index (dividing MLA height by truncated foot length), which is also is being used to classify feet in research. Weimar et al. (2013) suggested the normative MLA height for standing position is 6.00 ± 0.47 cm for the left foot and 6.05 ± 0.47 cm for the right foot following the study of seventy-nine collegiate females using AHIMS (Weimar & Shroyer, 2013). Butler et al. (2008) suggested the normal MLA height as 6.3 ± 0.6 cm for both feet in the standing position using the same AHIMS (Butler, Hillstrom, Song, Richards, & Davis, 2008).

Similar to the individuals with pronated and supinated feet, individuals with low or high arched feet are found to have complications in function and maintainence of balance (Fukano & Fukubayashi, 2009; Hertel et al., 2002; J.Hillstrom et al., 2013; Mootanah et al., 2013). Due to
various alterations in flat feet such as higher forefoot abduction, rear foot internal rotation, and greater peak plantar flexion during the late stance phase leading to excess pronation (Pazit-Levinger et al., 2010), their BOS can be considered unstable. Additionally, the increase in their lumbar curvature (Borges, Fernandes, & Bertoncello, 2013) may alter the COP which will eventually impact balance. Tahmasebi et al. (2014) reported that flat arched individuals are more unstable than normal individuals due to decreased proprioception, thereby leading to problems in bipedal stance predisposing to frequent falls (Razieh, Mohammad Taghi, Behnaz, & Francis, 2014). In 2017, Sung et al. found remarkably decreased dynamic stability in the individuals with a flat foot in unilateral stance in the eyes closed condition but not in the eyes open condition (Sung, Zipple, Andraka, & Danial, 2017). However, Pirouzi et al. (2014) concluded that there is no direct correlation found between the instability and the severity of the flatfoot (Pirouzi, Motealleh, Fallahzadeh, & Fallahzadeh, 2014). In addition, individuals with high arched feet have considerably greater COP excursion areas compared to individuals with rectus feet (Hertel et al., 2002). Therefore, they are more prone to postural instabilities similar to the individuals with pes planus. Tsai et al. (2006) and Cobb et al. (2014) have supported this hypothesis showing increased postural sway in high-arched individuals (Cobb et al., 2014; Tsai et al., 2006). Balance variations between the dominant leg and non-dominant leg is another important aspect which has drawn scientists’ interest. Hoffman et al. (1998) conducted a study on unilateral postural stability in functionally dominant and non-dominant legs on ten individuals with normal feet and found no significant difference in balance between the dominant and non-dominant legs (Hoffman, Schrader, Applegate, & Koceja, 1998). Similarly, in a study done by Clifford and Powell (2010) on twenty individuals with normal feet, there was no reported significant difference between the dominant and non-dominant legs (Clifford & Holder-Powell, 2010).
However, after the assessment of unilateral static balance in 40 track and field athletes, Knight et al. (2016) reported a significant amount of greater mediolateral displacement for the non-dominant limb, which may predispose this leg to a greater risk of injury (Knight, Holmes, Chander, Kimble, & Stewart, 2016).

**Quadriceps angle and its effect on postural stability**

The Q angle plays a major role both in the biomechanical function of the lower limb as well as in postural stability. It can be measured in the supine or standing position; and measuring it in the supine position is considered as the traditional method (T. Smith, Hunt, & Donell, 2008). In collegiate males, the average angle is 12.7° in the supine position and 13.6° in the standing position. In females, it is 15.8° in the supine position and 17.0° in the standing position (Woodland & Francis, 1992). In the standing position, angles greater than 15° in men and 20° in women are considered excessive (Hvid, Andersen, & Schmidt, 1981) and termed genu valgum deformity (knock knees). Angles smaller than the normal Q angles are considered as genu varum deformity (bowlegs) and the exact threshold values have not been established yet.

Plain radiographs, magnetic resonance imaging (MRI) and computed tomography (CT) are considered as the gold standards to assess the Q angle. Due to less expense, no radiation exposure, and convenience, goniometer measurements are preferred over radiological methods in the laboratory settings. Moreover, goniometry has been reported to be one of the best and accurate alternatives to radiography (Chevidikunnan Mohamed, Al Saif, Pai, & Mathias, 2017). The united pull exerted by the patellar tendon and the quadriceps femoris muscle group on the patella (Hungerford & Barry, 1979) become more pronounced with the greater Q angles (Horton & Hall, 1989). In addition, an increased Q angle causes patella mal-tracking towards the lateral side (patella is being pulled more laterally) (Hungerford & Barry, 1979). Contrarily, a decreased
angle may not cause medial mal-tracking of the patella, but the contact pressure of the medial tibiofemoral articulation might be increased due to an increase in the genu varum orientation (Mizuno et al., 2001). Therefore, the Q angle can be used as an indicator of knee joint malalignment, which is responsible for altering knee joint kinetics leading to poor balance. Since the Q angle is mainly considered regarding the knee pathologies, a minimal amount of literature is available on the impact of the Q angle on balance. Samaei et al. (2012) assessed static and dynamic balance in 90 college-aged females who were categorized into normal, genu valgum and genu varum groups according to the gap between the two knees. They have found an increase in postural sway in the mediolateral direction with genu varum deformity (Samaei, Bakhtiyari, Elham, & Rezasoltani, 2012). Similarly, a study done on fifty-eight elderly women showed an increased postural sway associated with higher Q angles than that of genu varum (Meira Mainenti et al., 2014). However, some researchers have found there is no association between Q angle and postural stability (Citaker et al., 2011). Therefore, future research studies are needed to assess the influence of Q angle on the biomechanical function of the lower limb and postural stability.

**Effect of foot type on Q angle**

The three segments in the human lower limb are the thigh, leg, and foot. The three main joints of hip, knee, and ankle have their own degrees of freedom in the frontal, sagittal and transverse planes. These three joints act together allowing the lower limb to move as a whole during quiet stance and locomotion. Therefore, it could be assumed that whenever there is an alteration to one segment or joint of the lower limb, the other segments would also undergo some alternations. Considering the anatomy and alignment of the lower limb, an indirect relationship between Q angle and MLA height/AHI could be expected. Supporting these assumptions, Khamis et al.
(2007) showed that there will be an escalation in knee valgus, internal rotation of the thigh and an alteration to the pelvic position with excessive foot pronation (Khamis & Yizhar, 2007). Furthermore, after analyzing the Q angle in 62 individuals, Sanchez et al. (2014) suggested that the value of the Q angle varies with the degree of external or internal rotation of the lower limb in the upright position (Sanchez, Sanchez, Baraúna, & Canto, 2014). Olerud and Berg (1984) assessed the Q angle using three different methods in different foot positions such as pronation, supination, inward, and outward rotation and concluded that the Q angle changes with the foot position (Olerud & Berg, 1984).

**Footwear and its effect on postural stability**

As a considerable extrinsic factor affecting balance, the impact of footwear and its design characteristics on balance have been studied widely. Chander et al. (2014) performed a study on 14 healthy college males on the effect of footwear (low top shoe, work boot and tactical boot) and workload on balance. It was found that the footwear with a higher shaft and a lower mass establish better balance (Harish Chander et al., 2014). Similarly, Debusk et al. (2018) studied the impact of a workload and two different types of shoes (standard and minimalist military boots) on bilateral and unilateral balance. They reported a lesser balance decrement with the standard boot and this was attributed to its design characteristics of thin/hard midsole, minimal heel drop, and the standard shaft height (DeBusk et al., 2018). Although balance in barefoot condition is found to be superior to that of shoes (D A Winter, 1995), minimalist or barefoot-like shoes have been introduced as the next best option with regard to the balance (Franklin, Grey, Heneghan, Bowen, & Li, 2015; B. S. Smith et al., 2015).
Vibram™ footwear and its effects on postural stability

Although the barefoot running is becoming increasingly popular, there is a possibility of compromising runner's foot health due to minor trauma like punctures, abrasions, and lacerations with barefoot running (Squadrone & Gallozzi, 2009). To address this problem, Vibram™ five fingers shoes (VFF) were introduced since it mimics the barefoot condition while protecting feet from injuries (Squadrone & Gallozzi, 2009). VFF is a thin, flexible minimalist type of shoe which has the exact contour of human feet. It possesses a separate slot for each toe which allows the independent position of toes within the footwear. It has a comparatively pliable sole to facilitate the anticipated movements of the feet. Hence, VFF is named minimalist shoes or “barefoot shoes”. Due to these features, VFF is considered as a bridge from unshod to shod conditions, therefore could be used to train individuals from unshod to shod in static conditions (B. S. Smith et al., 2015).

There are different types of VFF with varying features. Two such types of VFF are Vibram™ Bikila (VB) and Vibram™ Trek ascent (VT). Compared to VT, VB has a thinner and a harder sole (Table 2)(Figure 5). Since some studies done on other shoe types have shown more stability with thinner and harder soled shoes due to increased somatosensory feedback (D.Perry, AlisonRadtke, & R.Goodwin, 2007; Robbins et al., 1994), VB may make the athlete more stable than the VT. On the other hand, VT has some features which could favor better balance such as higher shaft, lacing and a certain tread pattern in the sole. However, due to the thin sole in VB, it has a possibility of causing stress fractures during jumping and running. Also, its thin sole may not provide adequate protection for running on the trails.
VFF has a limited amount of cushioning, minimal/no supporting materials in the heel, minimal/no heel drop and a thin and a hard sole compared to other athletic shoe types (Squadrone & Gallozzi, 2009). These features will increase somatosensory feedback and proprioception (B. S. Smith et al., 2015) and thereby assist in maintaining better stability. A study was done on occupational footwear on balance by Chander et al. (2014) and a study was conducted on firefighter boots by Garner et al. (2013) individually showed that the increased weight of the footwear during a workload will deteriorate postural stability (Harish Chander et al., 2014; Garner et al., 2013). Since VFF has a minimal weight compared to other athletic shoe types (Squadrone & Gallozzi, 2009), VFF may assist in a better balance than other athletic footwear types. The study that was done by Chander et al. (2016) substantiates this theory. They studied eighteen participants' balance before and after a workload in thong style flip-flops, clog style Crocs® and VFF. There was a greater balance performance in VFF than other shoe types.
(Harish Chander et al., 2016). After analyzing the static balance of 49 participants using Biodex Stability System™, Smith et al. (2015) showed that VFF elicits higher postural stability than barefoot condition (B. S. Smith et al., 2015). Chander et al. (2016) analyzed static balance using postural sway variables and postural response latencies using the sensory organization test (SOT) on the NeuroCom Equitest System™ and showed that minimalist footwear like VFF elicits considerably higher postural stability than Crocs© and Flip Flops (Harish Chander et al., 2016).

Additionally, VFF is found to be associated with better performance capabilities than standard running shoe type (Squadrone & Gallozzi, 2009). However, Miller et al. (2014) suggested that wearing minimalist shoes could cause higher demands on the muscles that compose the arch (Miller, Whitcome, Lieberman, Norton, & Dyer, 2014). This could alter the normal distribution of forces acting on the foot and therefore impact balance. Additionally, VFF is not specifically designed for abnormal foot types. Therefore, a positive impact of VFF in individuals with a pronated or supinated foot is arguable. However, to the best of author’s knowledge, as of today, no literature is available on comparison of two or more types of VFF and its effect on balance.

**Conclusion**

Static balance could be alerted with different intrinsic factors such as anatomical variations of the feet (foot posture, MLA height, AHI), alignment of the lower extremity (genu valgum, genu varum), and vision as well as with extrinsic factors such as nature of standing surface, BOS, and footwear. In the literature described in this chapter has shown different theories and concepts related to postural stability, foot type, Q angle, and VFF footwear. Certainly, all these aspects have overlapping effects with the possibility of affecting balance, performance, and injury risk. There is a recognizable gap in the literature, especially when considering Q angle and VFF,
which cannot be ignored. Therefore, this study addresses some of those aspects such as the effects of foot type, Q angle, VFF, and its design characteristics on balance.
CHAPTER III
METHODOLOGY

Participants
After obtaining approval from the Mississippi State University (MSU) Institutional Review Board (IRB), 24 recreationally active college-aged males with no history of musculoskeletal, neurological, visual, vestibular abnormalities or pathologies and with no prior exposure to VFF were recruited (Table 1). Participants were recruited with the use of flyers on bulletin boards on the MSU Department of Kinesiology, Joe Frank Sanderson Center, and in the Mitchel Memorial Library as well as an announcement via email to all Kinesiology students in MSU. Individuals who perform aerobic exercise 3-4 days/week (150min) and resistance training at least 2 days/week for at least the last 3 months was considered as recreationally trained (Ferguson, 2014). After completing the informed consent, participants filled out a Physical Activity Readiness Questionnaire (PAR-Q) (Appendix B) to assess any existing risk factors. Individuals who had bilateral feet classified into different foot type categories were excluded from the study. Sample size was calculated using G-Power statistical software with the desired power of 0.8, an effect size of 0.25 and an alpha level of 0.05.
Table 1

Participants’ demographic data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>21.38 ± 2.50</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.74 ± 0.06</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>71.24 ± 10.37</td>
</tr>
<tr>
<td>BMI (kg/m$^2$)</td>
<td>23.58 ± 3.62</td>
</tr>
<tr>
<td>Shoe size</td>
<td>10.65 ± 0.84</td>
</tr>
</tbody>
</table>

**Study Design**

The study followed a repeated measures design with a counterbalanced footwear assignment. Participants were tested in the barefoot condition first followed by two types of Vibram™ five fingers footwear; Vibram™ Bikila (VB) and Vibram™ Trek ascent (VT)(Figure 6).

**Instrumentation**

Participants’ height (m) and mass (kg) were measured with a portable stadiometer. Bilateral MLA height (cm) and truncated foot length (cm) were measured with an AHIMS (Jacktool®, NJ, USA) (Figure 7) and AHI was calculated. Q angle (degrees) was measured using a digital goniometer (Medigauge®, Taylor Toolworks, MO, USA) (Figure 8). Sole hardness (Shore A durometer units) of two shoe types was measured using Shore A portable durometer (Figure 9). Sole thickness (mm) was measured with callipers (Figure 10). Other dimensions of the VFF footwear such as heel height (cm), and shaft height (cm) were measured using a tape measure for recording purpose (Table 2).
Figure 6. Vibram™ Bikila (left) and Vibarm™ Trek Ascent (right) demonstrating the sole thickness and shaft height

Figure 7. Arch height index measurement system (right foot)- MLA height
Table 2

*Design characteristics of Vibram™ Bikila and Vibram™ Trek ascent*

<table>
<thead>
<tr>
<th></th>
<th>Vibram™ Bikila</th>
<th>Vibram™ Trek ascent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (g)</td>
<td>168.4</td>
<td>173.5</td>
</tr>
<tr>
<td>Midsole hardness (Shore A durometer units)</td>
<td>74.7</td>
<td>63.45</td>
</tr>
<tr>
<td>Sole thickness (mm)</td>
<td>3.35</td>
<td>6.73</td>
</tr>
<tr>
<td>Heel height (cm)</td>
<td>2.1</td>
<td>3.2</td>
</tr>
<tr>
<td>Shaft height at ankle (cm)</td>
<td>5.1</td>
<td>7.4</td>
</tr>
<tr>
<td>Lacing</td>
<td>(-)</td>
<td>(+)</td>
</tr>
<tr>
<td>Treads in the sole</td>
<td>Lesser number of larger treads, no treads in the middle-medial part of the sole</td>
<td>Greater number of smaller treads, distributed over the entire sole</td>
</tr>
</tbody>
</table>
Experimental procedures

After collecting the anthropological data, MLA height and Q angle were measured and the FPI was determined using FPI-6. According to the FPI, the participants were categorized into neutral (n=8), supinated (n=8) and pronated (n=8) groups. As an individuals balance is found not to be significantly different between the dominant leg and the non-dominant leg (Clifford & Holder-Powell, 2010; Hoffman et al., 1998), each participants unilateral balance was assessed only for
the dominant leg. Each participants functional leg dominance was determined using the ball-kick test, step-up test, and balance recovery test (Hoffman et al., 1998; W.-H. Lin, Liu, Hsieh, & Lee, 2009; Yeung, Chan, So, & Yuan, 1994). Following the allocation of footwear, participants were familiarized with the experimental procedures and their questions were answered. At the end of the familiarization session, the participants were scheduled for their balance assessment on their next convenient day and were advised not to do lower body strength training on the day before their scheduled session.

![Figure 11. Unilateral balance testing on stable surface with Vibram™ Bikila (Left); Bilateral balance testing on unstable surface with Vibram™ Trek Ascent (Right)](image)

During the balance assessment session, the participants’ static balance in the barefoot condition was assessed first followed by the two types of footwear in a counterbalanced order to minimize the order effects. There was a ten-minute washout period between each footwear condition.
Balance was assessed using an AMTI™ (AMTI AccuGait, Watertown, MA, USA) force platform for three trials under the following four testing conditions for both the stable and unstable surface: bipedal eyes open (BLEO), bipedal eyes closed (BLEC), unipedal (dominant leg) eyes open (ULEO), unipedal (dominant leg) eyes closed (ULEC). Data was collected for 20s in each EO condition and 10s for each EC condition. During data collection, the participants were advised to stay as motionless as possible in an erect standing position on the force plate with arms suspended along the sides of the body and their eyes fixed on a specific point. At the end of each footwear testing block, the participants perception of balance was verbally assessed (Appendix B). The whole study was carried out in the Neuromechanics Laboratory at MSU.

**Statistical Analysis**

Postural sway variables of interest were COP-X average (cm), COP-Y average (cm), average displacement along X axis (cm), average displacement along Y axis (cm), 95% ellipse area ($cm^2$), and average sway velocity (cm/s). Postural sway variables for all conditions [for stable and unstable surface; bipedal eyes open (BLEO), bipedal eyes closed (BLEC), unipedal (dominant leg) eyes open (ULEO), unipedal (dominant leg) eyes closed (ULEC)] were analyzed using a 3 (foot type) × 3 (footwear type) between subjects repeated measures analysis of variance (ANOVA) individually. Any main effect significance was further analyzed with post hoc pairwise comparisons using Bonferroni correction factor. Additionally, Pearson product correlational analyses were performed for Q angle, MLA height, and AHI with postural sway variable in the BF condition as well as for Q angle with MLA height and AHI. All analyses were done in SPSS V25 with an a priori level 0.05.
CHAPTER IV

RESULTS

Footwear and postural stability

The results of the repeated measures ANOVA revealed significant main effect differences between footwear in average displacement along Y axis in stable, BLEO condition (F(2, 42) = 3.481; p = 0.0400; η² = 0.142). Post hoc comparisons revealed a significantly lower displacement along Y axis for the barefoot condition compared to VB (Figure 12).

![Figure 12. Average displacement along Y axis in the stable bilateral eyes open (BLEO) condition. * represent the significant differences between footwear. Bars represent the standard error. BF: Barefoot, VB: Vibram™ Bikila, VT: Vibram™ Trek Ascent](image)

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There was a significant main effect for footwear in COP-Y average in stable BLEC condition (F(2, 42) = 4.961; p = 0.012; η² = 0.191). Post hoc comparisons revealed a significantly lower COP-Y average with VT compared to VB (Figure 13).

In the stable ULEC condition, a significant footwear main effect was seen in the average displacement along X-axis (F(2, 42) = 3.980; p = 0.026; η² = 0.159). Pairwise comparisons did not reveal a significant difference but were approaching significance (p = 0.071) indicating lower average displacement along X axis in barefoot condition compared to VB (Figure 14).

![Figure 13. COP-Y average in the stable bilateral eyes closed (BLEC) condition. * represent the significant differences between footwear. Bars represent the standard error. BF: Barefoot, VB: Vibram™ Bikila, VT: Vibram™ Trek Ascent](image-url)
Figure 14. Average displacement along X axis in the stable unilateral eyes closed (ULEC) condition. Bars represent the standard error. BF: Barefoot, VB: Vibram™ Bikila, VT: Vibram™ Trek Ascent.

Figure 15. 95% ellipse area in the stable unilateral eyes closed (ULEC) condition. Bars represent the standard error. BF: Barefoot, VB: Vibram™ Bikila, VT: Vibram™ Trek Ascent.
Similarly, in stable ULEC condition, a significant footwear main effect was seen in 95% ellipse area ($F(2, 42) = 4.418; p = 0.018; \eta^2 = 0.174$). Pairwise comparisons were approaching significance ($p = 0.056$) indicating a lower 95% ellipse area in the barefoot condition than VB (Figure 15).

There was a significant main effect footwear difference in COP-Y average in unstable BLEO condition ($F(2, 42) = 5.683; p = 0.007; \eta^2 = 0.213$). Post hoc comparisons revealed a significantly lower COP-Y average with barefoot compared to VB (Figure 16).

A significant main effect footwear difference was seen in COP-Y average in unstable BLEC condition ($F(2, 42) = 8.131; p = 0.001; \eta^2 = 0.279$). Post hoc comparisons demonstrated a significantly lower COP-Y average for the barefoot condition compared to both VB and VT. Post hoc tests did not reveal a significant difference between VB and VT (Figure 17).

**Figure 16.** COP-Y average in the unstable bilateral eyes open (BLEO) condition. * represent the significant differences between footwear. Bars represent the standard error. BF: Barefoot, VB: Vibram™ Bikila, VT: Vibram™ Trek Ascent
Figure 17. COP-Y average in the unstable bilateral eyes closed (BLEC) condition. * represent the significant differences between footwear. Bars represent the standard error. BF: Barefoot, VB: Vibram™ Bikila, VT: Vibram™ Trek Ascent

In the condition of unstable ULEO, a significant footwear main effect was seen in average displacement along Y axis (F(2, 42) = 0.201; p = 0.000; η² = 0.305). Post hoc comparisons revealed a significantly lower displacement along the Y axis with VB and VT compared to the
Table 3

Comparison of statistics [mean (standard deviation)] for barefoot (BF), Vibram™ Bikila (VB), and Vibram™ Trek Ascent (VT) from static balance analysis in stable and unstable surfaces, in bilateral eyes open (BLEO), bilateral eyes closed (BLEC), unilateral eyes open (ULEO), and unilateral eyes closed (ULEC) conditions. Table contains the sway variables with footwear main effects, * denotes significant footwear differences

<table>
<thead>
<tr>
<th>Variable</th>
<th>BF mean (SD)</th>
<th>VB mean (SD)</th>
<th>VT mean (SD)</th>
<th>F</th>
<th>p-value</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stable BLEO</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average displacement along Y (cm)</td>
<td>0.38 (0.10)*</td>
<td>0.40 (0.09)</td>
<td>0.44 (0.12)*</td>
<td>3.481</td>
<td>0.040</td>
<td>0.142</td>
</tr>
<tr>
<td>COP-Y average (cm)</td>
<td>3.68 (1.77)</td>
<td>4.52 (1.88)*</td>
<td>3.70 (2.14)*</td>
<td>4.961</td>
<td>0.012</td>
<td>0.191</td>
</tr>
<tr>
<td><strong>Stable ULEC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average displacement along X (cm)</td>
<td>0.79 (0.17)</td>
<td>0.90 (0.15)</td>
<td>0.87 (0.16)</td>
<td>3.98</td>
<td>0.026</td>
<td>0.159</td>
</tr>
<tr>
<td>95% Ellipse Area (cm.cm)</td>
<td>20.57 (7.51)</td>
<td>25.96 (7.26)</td>
<td>25.01 (10.11)</td>
<td>4.418</td>
<td>0.018</td>
<td>0.174</td>
</tr>
<tr>
<td><strong>Unstable BLEO</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COP-Y average (cm)</td>
<td>2.80 (1.47)*</td>
<td>3.82 (1.45)*</td>
<td>3.27 (1.62)</td>
<td>5.683</td>
<td>0.007</td>
<td>0.213</td>
</tr>
<tr>
<td><strong>Unstable BLEC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COP-Y average (cm)</td>
<td>2.48 (1.70)*</td>
<td>3.47 (1.52)*</td>
<td>3.82 (1.74)*</td>
<td>8.131</td>
<td>0.001</td>
<td>0.279</td>
</tr>
<tr>
<td><strong>Unstable ULEO</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average displacement along Y (cm)</td>
<td>0.92 (0.25)*</td>
<td>0.8 (0.15)*</td>
<td>0.79 (0.18)*</td>
<td>0.201</td>
<td>0.000</td>
<td>0.305</td>
</tr>
<tr>
<td>95% Ellipse Area (cm.cm)</td>
<td>18.00 (6.97)*</td>
<td>15.81 (3.78)</td>
<td>15.19 (4.70)*</td>
<td>3.949</td>
<td>0.027</td>
<td>0.158</td>
</tr>
<tr>
<td><strong>Unstable ULEC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average displacement along Y (cm)</td>
<td>1.38 (0.33)*</td>
<td>1.58 (0.38)*</td>
<td>1.52 (0.34)</td>
<td>3.399</td>
<td>0.043</td>
<td>0.139</td>
</tr>
<tr>
<td>95% Ellipse Area (cm.cm)</td>
<td>38.34 (12.42)*</td>
<td>46.55 (15.25)*</td>
<td>45.45 (14.22)</td>
<td>4.177</td>
<td>0.022</td>
<td>0.166</td>
</tr>
</tbody>
</table>
barefoot condition. Post hoc tests did not reveal a significant difference between VB and VT (Figure 18).

*Figure 18.* Average displacement along Y axis in the unstable unilateral eyes open (ULEO) condition. * represent the significant differences between footwear. Bars represent the standard error. BF: Barefoot, VB: Vibram™ Bikila, VT: Vibram™ Trek Ascent
Similarly, in the same condition, a significant footwear main effect was evident in 95% ellipse area (F(2, 42) = 3.949; p = 0.027; η² = 0.158). There was a lower 95% ellipse area in VB and VT compared to barefoot condition evident from the pairwise comparisons. No significant difference was shown between VB and VT (Figure 19).
During unstable ULEC condition, a significant footwear main effect was seen for both average displacement along Y axis ($F(2, 42) = 3.399; p = 0.043; \eta^2 = 0.139$) and 95% ellipse area ($F(2, 42) = 4.177; p = 0.022; \eta^2 = 0.166$). According to the post hoc comparisons, the barefoot condition demonstrated a lower average displacement along the Y-axis and 95% ellipse area compared to VB (Figure 20, Figure 21) (Table 3).

There were no significant differences found in COP-X average and in average sway velocity variables under any situations. No violation of Mauchly’s test of sphericity was reported in any of the conditions.
Figure 21. 95% ellipse area in the unstable unilateral eyes closed (ULEC) condition. * represent the significant differences between footwear. Bars represent the standard error. BF: Barefoot, VB: Vibram™ Bikila, VT: Vibram™ Trek Ascent

Foot type and postural stability

Postural sway variables were analyzed for different testing conditions with regard to the three different foot types (neutral, supinated, and pronated). There were no significant differences found between the foot types for any postural sway variables under any condition. There were no footwear * foot type interactions.

Q angle and postural stability

Pearson product correlation analysis did not reveal any significant correlations between the participants dominant leg Q angle and postural sway variables in the unilateral balance assessment in BF conditions.
MLA height and postural stability

Pearson product correlation analysis did not reveal any significant correlation between participants’ dominant leg MLA height and postural sway variables in the unilateral BF conditions.

Correlation between Q angle and AHI

Pearson product correlation analysis revealed a significant negative correlation \( (r = -0.420; p = 0.020) \) between participants’ dominant leg Q angle and AHI.

Correlation between Q angle and MLA height

Pearson product correlation analysis did not reveal any significant correlation between participants’ dominant leg Q angle and MLA height.

Qualitative feedback on footwear conditions

Regardless of the foot type, 20.83% of the participants rated the barefoot condition, 33.33% of the participants rated VB, 29.17% of the participants rated VT, and 16.67% participants rated VB=VT as the best perception of balance.

Similarly, regardless of the foot type, 41.67% of the participants rated barefoot condition, 12.50% of the participants rated VB, 33.33% of the participants rated VT, and 12.50% participants rated barefoot condition=VT as the worst perception of balance.

Number of failed trails

In barefoot unstable ULEC condition, two participants with neutral feet, two participants with pronated feet, and two participants with supinated feet failed to complete the trial. In VB unstable ULEC condition, one participant with neutral feet, one participant with pronated feet, and two participants with supinated feet failed to complete the trial. Similarly, in VT unstable
ULEC condition, three participants with neutral feet, and two participants with supinated feet failed to complete the trial.
CHAPTER V
DISCUSSION

The purpose of this study was to investigate the impact of foot type, Q angle, and two types of Vibram™ five fingers footwear (VB and VT) on static postural stability in healthy college-aged males. Foot type classification using the FPI-6 and the Q angle were chosen due to lack of literature regarding static balance performance. VFF was chosen due to the high demand in athletic populations. As there were no studies done on static balance performances in different types of VFF, two types of VFF (VB and VT) were selected for comparison. It was hypothesized that a significant difference in static balance would be seen between the different foot types and Q angles due to anatomical variations leading to alterations in balance. Also, it was hypothesized there would be a significant difference in postural stability between the barefoot and shod conditions due to alterations in somatosensory feedback. Differences in static balance between the two VFF footwear was hypothesized due to design characteristics of the footwear. Additionally, a significant correlation between Q angle and MLA height/AHI was hypothesized considering the lower extremity as a whole and assuming an alteration to one alignment would change the other alignments of the lower limb.

Extrinsic factors that affect postural stability

Type of footwear

In the current study, footwear was studied as the extrinsic factor that affects postural stability. Regardless of the foot type, all the testing conditions except unstable ULEO condition
demonstrated a significant footwear main effect (significant differences were found for the stable BLEO, stable BLEC, stable ULEC, unstable BLEO, unstable BLEC and unstable ULEC conditions) justifying the importance of footwear in postural control. In the different balance conditions, stable BLEO, unstable BLEO, unstable BLEC, and unstable ULEC, barefoot condition demonstrated significantly lesser average displacement along Y axis, COP-Y average, and 95% ellipse area than shod conditions. In the stable ULEC condition, the pairwise comparisons were approaching significance showing lesser values in average displacement along X axis and 95% ellipse area for the barefoot condition compared to the shod condition. The insignificance in pairwise comparisons could be due to the lower sample size. COP-Y average and average displacement along Y-axis represent the postural sway in the anteroposterior direction, average displacement along X-axis represents the postural sway in the mediolateral direction and 95% ellipse area represents the COP displacement within a 95% confidence ellipse. Therefore, the lesser values for the aforementioned sway variables demonstrates a lesser balance decrement, or better balance. Therefore, in the conditions of stable BLEO, unstable BLEO, unstable BLEC, stable ULEC, and unstable ULEC, barefoot can be considered more superior than the shod conditions regarding balance performance. This could be explained with having the highest somatosensory feedback in the barefoot condition without any obliteration from a shoe sole. This finding agrees with many of the previous studies which have shown the best postural stability in the barefoot condition (Alghadir et al., 2018; Shinohara & Gribble, 2019). Alghadir et al. (2018) conducted a very similar study examining the static balance in 30 young healthy males in barefoot and two shod conditions (sandal and standard shoe) and have reported lower postural sway in the unshod condition compared to the balance in the sandals (Alghadir et al., 2018). Similarly, Shinohara & Gribble (2019) studied static balance
in 20 young, healthy individuals in five-toes socks, regular socks and barefoot. Although the socks were very thin, participants demonstrated greater postural stability in the barefoot condition (Shinohara & Gribble, 2019).

In the unstable ULEO condition, regardless of the foot type, there was a significant footwear main effect for the average displacement along the Y-axis and in the 95% ellipse area. For the pairwise comparisons, there was a lower average displacement along Y-axis; indicating a smaller anteroposterior displacement and lower 95% ellipse area; indicating that the individuals stayed closer to the center of the platform with VT compared to barefoot condition. In addition, in the same condition, pairwise comparisons revealed lower average displacement along Y-axis; indicating a smaller anteroposterior displacement with VB compared to the barefoot condition.

According to these findings, it could be concluded that in more challenging conditions such as standing on an unstable surface with a minimal BOS (UL stance), any type of shoe would potentially be better than the barefoot condition. This could be due to the design characteristics of the footwear, such as the provision of higher somatosensory feedback due to the ankle support in both footwear. This concept was proven by Squadrone & Gallozzi (2011) after comparison of foot movements in barefoot conditions and in VFF. They mentioned that footwear like VFF increases the ankle joint position sense and better perception of ankle range of motion (Squadrone & Gallozzi, 2011). In addition, the lesser balance decrements with footwear could also be due to an increased BOS provided by the footwear compared to the barefoot condition. These results support the previous literature on VFF eliciting better balance than the barefoot condition. Supporting theis concept, Smith et al. (2015) studied 49 healthy adults static balance in a barefoot condition, VFF and athletic shoes. VFF has demonstrated greater overall static balance and greater anteroposterior static balance compared to the barefoot condition (B. S. S.}{\text{\textnumero}}
Smith et al., 2015). Therefore, the findings suggest that in a situation where the somatosensory feedback is distorted (unstable surface), having an extra amount of somatosensory feedback or a minimal increase in the BOS even on a single leg is advantageous, hence any type of footwear is preferred over a barefoot condition.

Overall, according to the descriptive statistics, VT has lesser decrements to postural stability compared to VB, which could be attributed to its design features such as higher shaft (ankle support) providing more somatosensory feedback due to the compression around ankle, specific tread pattern (higher number of smaller treads distributed over the entire sole)(figure 22), presence of lacing which aids in securing the shoe to the foot. However, except for the COP-Y average in the stable BLEC condition, there was no significant difference between VB and VT as evidenced by the pairwise comparisons. In the aforementioned condition, VT showed lesser COP-Y average (lesser displacement along anteroposterior direction) than VB. This suggests that these two types of footwear are relatively similar with regard to the balance, hence the barefoot condition is the best for maintaining static postural stability in young healthy males. However, since VT demonstrated a greater balance performance in unstable ULEO condition than the barefoot condition, higher balance in the stable BLEC condition than VB, and overall lesser decrements to postural sway parameters than VB, VT could be considered as the next best option after the barefoot condition.
Considering the number of failed trials, regardless of the foot type, performing the unstable ULEC condition was more challenging in all three footwear conditions. This could be due to the unstable surface interfering with somatosensory feedback and the narrower BOS causing difficulty in maintaining balance.

**Intrinsic factors that affect postural stability**

**Foot type**

Although it was hypothesized that the foot type would affect static balance, the results showed no significant difference between the neutral, pronated and supinated foot types. This could be due to the use of FPI-6 which might not be the best way to categorize foot type. This was encountered by other researchers as well. Some investigators who studied the applicability and reliability of the modified FPI (FPI-6) have concluded that the use of FPI-6 in research is uncertain (Evans et al., 2003). In addition, the insignificant results between foot types could be due to the inexperience of the observer. Although the FPI in the individuals were assessed by the same observer, Cornwall et al. (2008) have suggested a possible learning effect within the first
20 feet examined during the FPI assessment, therefore this should be interpreted with extreme caution in research (Cornwall et al., 2008). This has been experienced by some previous investigators who have not found an impact of foot type on balance (Heggannavar et al., 2016; Mohd Said et al., 2015). In addition, the lower sample size (n=8 in each foot type) could be a reason for the results in the current study, similar to the Heggannavar et al., 2016 (Heggannavar et al., 2016).

There was an attempt to categorize participants’ feet for the present study using AHI and MLA height according to the normative values suggested by Butler et al., 2008 (Butler et al., 2008). However, according to the AHI, 14 participants were classified as having normal feet and according to the MLA height, 18 participants were classified as having normal feet. Therefore, the FPI-6 was used for foot classification.

**Q angle**

It was hypothesized that Q angle would affect the unilateral balance in the barefoot condition regardless of the foot type. However, the results did not show an impact of Q angle on unilateral balance. This could be due to the recruitment of only males, who did not have much variability among the Q angles (mean = 8.70°; SD = 2.08°). This lies well below the normative value of Q angle set for males in the standing position, which is 13.6° (Woodland & Francis, 1992). Q angle is proven to be higher in females than males (Horton & Hall, 1989; Woodland & Francis, 1992) and therefore more prone to Q angle related abnormalities (Horton & Hall, 1989; Mizuno et al., 2001). Therefore, if there were female participants in the current study, a correlation may have been seen. However, a study which was done on static balance in 50 females with patellofemoral pain syndrome did not show a relationship between Q angle and unilateral static balance (Citaker et al., 2011).
MLA height/AHI

Similarly, the impact of MLA height on unilateral postural stability in the barefoot condition was hypothesized regardless of the foot type. However, results did not show any impact of MLA/AHI height on unilateral balance. This result could be due to 75% of participants falling in the normal category after classifying them with the MLA height with a minimal variability (mean = 6.78 cm; SD = 0.41 cm) and 58% participants falling into the normal category with AHI.

Correlation between Q angle and AHI/MLA height

As hypothesized, Pearson product correlation revealed a significant moderate correlation between Q angle and AHI. It was found to be a negative correlation which was suggested by the other investigators (Khamis & Yizhar, 2007; Mitani, 2017). Mitani (2017) studied 224 college-aged athletes (154 males and 70 females) on the gender variations in lower extremity anatomy. She calculated the AHI by dividing navicular bone height by the foot length and measured the Q angle using a goniometer. Although it is not clear whether she found a correlation between AHI and Q angle, she concluded that females have a significantly higher Q angle and a significantly lower AHI than males indicating a negative correlation (Mitani, 2017). However, in the present study, there was no correlation shown between the MLA height and the Q angle. Therefore, it could be assumed that even in a sample in which 75% of the participants’ MLA height falls in the normal category, AHI measured using the AHIMS could be a more reliable and appropriate variable which could be used for lower extremity anatomical assessments.

Qualitative feedback on footwear conditions

Regardless of the foot type, the lowest percentage of participants (20.83%) rated barefoot as the best perception of balance and highest percentage of participants (41.67%) rated barefoot as the worst perception of balance. Contrarily, the highest percentage of participants (33.33%) rated
VB as the best perception of balance and lowest percentage of participants (12.50%) rated VB as the worst perception of balance. However, these subjective perceptions were found to be the exact opposite of the objective analysis; postural stability was best in the barefoot condition and in the worst in VB. Therefore, in selecting a footwear considering balance performance, the subjective preference and comfort should not be in the primary factor. There are many other design characteristics which determine the ability to maintain optimum stability.

**Limitations and future research**

The main limitation of the study was the smaller sample size (eight participants in each foot category). There was a difficulty recruiting participants with three different foot types who could fit into the limited male shoe sizes available (9 ½ to 12). Another limitation is the use of only male participants for the study which could be improved with the recruitment of female participants for future studies. Additionally, VFF is mainly used for outdoor running, yoga and water sports, therefore the results observed for static postural stability may not be applicable to those situations. Therefore, assessing dynamic balance (gait, slips, jumps, running) and studying participants outside the laboratory could be a valuable addition for future research. Also, this study was done on first exposure to VFF, which could be developed to assess the adaptation/learning effects with VFF.
Conclusion

The purpose of this study was to investigate the impact of foot type, Q angle, and two types of Vibram™ five fingers footwear (VB and VT) on static postural stability in healthy college-aged males. Based on the findings, it could be concluded that the barefoot condition is superior to the shod condition in all situations investigated except the unstable ULEO condition, which VT showed a greater balance performance attributed to its design characteristics. Therefore, in a most challenging situation such as on unstable surface and in the UL stance, the barefoot condition may not be the best option to achieve the best postural stability. Q angle, MLA height and AHI did not affect unilateral balance in BF condition. In addition, no significant difference in balance was found among different foot types suggesting that the FPI-6 may not the best method of classifying feet. Therefore, further research with different foot classification methods are needed to analyze the impact of foot type on static postural stability.
REFERENCES


https://doi.org/10.16965/ijpr.2016.127


https://doi.org/10.1093/ageing/afl077


APPENDIX A

FOOT POSTURE INDEX-6
Table A1

*Foot posture index 6 scoring (A. Redmond, 2005)(A. C. Redmond et al., 2006)*

<table>
<thead>
<tr>
<th>Component</th>
<th>Plane</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talar head palpation</td>
<td>Transverse</td>
<td>Palpable laterally, not palpable medially</td>
<td>Palpable laterally, slightly palpable medially</td>
<td>Equally palpable on both sides</td>
<td>Slightly palpable laterally, palpable medially</td>
<td>Not palpable laterally, palpable medially</td>
</tr>
<tr>
<td>Supra lateral malleoli curvature (SLMC) and infra malleoli curvature (ILMC) inspection</td>
<td>Frontal/Transverse</td>
<td>ILMC is straight or convex</td>
<td>ILMC is concave but flatter than SLMC</td>
<td>Both curves roughly equal</td>
<td>ILMC is more concave than SLMC</td>
<td>ILMC is markedly concave than SLMC</td>
</tr>
<tr>
<td>Calcaneal frontal plane position inspection</td>
<td>Frontal</td>
<td>More than an estimated 5° inverted</td>
<td>Between vertical and an estimated 5° inverted</td>
<td>Vertical</td>
<td>Between vertical and an estimated 5° everted</td>
<td>More than an estimated 5° everted</td>
</tr>
<tr>
<td>Component</td>
<td>Plane</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>------------</td>
<td>------------------------</td>
<td>-------------------------</td>
<td>--------------</td>
<td>------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Talo-navicular joint (TNJ) prominence inspection</td>
<td>Transverse</td>
<td>Prominently concave</td>
<td>Slightly, but definitely concave</td>
<td>Flat</td>
<td>Bulging slightly</td>
<td>Bulging markedly</td>
</tr>
<tr>
<td>Congruence of MLA inspection</td>
<td>Sagittal</td>
<td>Arch is high and angled towards the posterior end of the MLA</td>
<td>Arch is moderately high and slightly acute posteriorly</td>
<td>Arch height normal and concentrically curved</td>
<td>Arch is low with some flattening in the central position</td>
<td>Arch is very low (makes ground contact) with marked flattening centrally</td>
</tr>
<tr>
<td>Abduction/adduction of forefoot on rearfoot inspection</td>
<td>Transverse</td>
<td>Lateral toes are not visible. Medial toes are clearly visible</td>
<td>Medial are toes clearly more visible than lateral toes</td>
<td>Medial and lateral toes equally visible</td>
<td>Lateral toes clearly more visible than medial</td>
<td>Medial toes are not visible. Lateral toes are clearly visible.</td>
</tr>
</tbody>
</table>
Foot posture index 6 assessing steps (A. Redmond, 2005)

Step 1- Talar head palpation

Step 2- Supra lateral malleoli curvature and infra malleoli curvature inspection
Step 3- Calcaneal frontal plane position inspection

Step 4- Talo-navicular joint (TNJ) prominence inspection
Step 5 - Congruence of MLA inspection

Neutral (0)

Supinated foot (-2)

Pronated foot (+2)
Step 6- Abduction/adduction of forefoot on rearfoot inspection

<table>
<thead>
<tr>
<th>Supinated (-2)</th>
<th>Neutral (0)</th>
<th>Pronated (+2)</th>
</tr>
</thead>
</table>

[Images of foot positions: Supinated, Neutral, Pronated]
APPENDIX B

QUESTIONNAIRES
Physical Activity Readiness Questionnaire (PAR-Q)

NAME: _______________________________ DATE: ________________
HEIGHT: _______ in. WEIGHT: _________ lbs. AGE: _______

1) Has your doctor ever said that you have a heart condition and that you should only perform
   physical activity recommended by a doctor?

2) Do you feel pain in your chest when you perform physical activity?

3) In the past month, have you had chest pain when you were not performing any physical
   activity?

4) Do you lose your balance because of dizziness or do you ever lose consciousness?

5) Do you have a bone or joint problem that could be made worse by a change in your physical
   activity?

6) Is your doctor currently prescribing any medication for your blood pressure or for a heart
   condition?

7) Do you know of any other reason why you should not engage in physical activity?

GENERAL & MEDICAL QUESTIONNAIRE

Occupational Questions

1) What is your current occupation?

2) Does your occupation require extended periods of sitting?

3) Does your occupation require extended periods of repetitive movements? (If yes, please
   explain.)

4) Does your occupation require you to wear shoes with a heel (dress shoes)?

5) Does your occupation cause you anxiety (mental stress)?

Recreational Questions
6) Do you partake in any recreational activities (golf, tennis, skiing, etc.)? (If yes, please explain.)

7) Do you have any hobbies? (If yes, please explain.)

Medical Questions

8) Have you ever had any pain or injuries (ankle, knee, hip, back, shoulder, etc.)? (If yes, please explain.)

9) Have you ever had any surgeries? (If yes, please explain.)

10) Has a medical doctor ever diagnosed you with a chronic disease, such as coronary heart disease, coronary artery disease, hypertension (high blood pressure), high cholesterol or diabetes? (If yes, please explain.)

11) Are you currently taking any medication? (If yes, please list.)
Verbal qualitative feedback questions for the participants

After barefoot testing and VB testing,

Q1. Compared to without shoes, how did you feel about your balance in white color shoes (VB)
   - easier to maintain balance with white color shoes than without shoes
   - difficult to maintain balance with white color shoes than without shoes
   - did not feel any difference
   - do not have an idea

After barefoot testing and VT testing,

Q2. Compared to without shoes, how did you feel about your balance in black color shoes (VT)
   - easier to maintain balance with black color shoes than without shoes
   - difficult to maintain balance with black color shoes than without shoes
   - did not feel any difference
   - do not have an idea

After VB testing and VT testing,

Q3. Compared to white color shoes (VB), how did you feel about your balance in black color shoes (VT)
   - easier to maintain balance with white color shoes than black color shoes
   - difficult to maintain balance with white color shoes than black color shoes
   - did not feel any difference
   - do not have an idea

In the case they underwent VT testing before VB, the opposite questions were asked [eg:

Compared to black color shoes (VT), how did you feel about your balance in white color shoes (VB)]
APPENDIX C

DESCRIPTIVE STATISTICS TABLES
### Descriptive statistics tables

Table C1

*Descriptive statistics for average displacement along Y in the stable bilateral eyes open (BLEO) for barefoot (BF), Vibram™ Bikila, Vibram™ Trek Ascent according to the foot types neutral (N), supinated (S) and pronated (P)*

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BF</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>0.37</td>
<td>0.09</td>
</tr>
<tr>
<td>S</td>
<td>0.41</td>
<td>0.13</td>
</tr>
<tr>
<td>P</td>
<td>0.38</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>VB</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>0.40</td>
<td>0.10</td>
</tr>
<tr>
<td>S</td>
<td>0.38</td>
<td>0.09</td>
</tr>
<tr>
<td>P</td>
<td>0.41</td>
<td>0.09</td>
</tr>
<tr>
<td><strong>VT</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>0.47</td>
<td>0.13</td>
</tr>
<tr>
<td>S</td>
<td>0.46</td>
<td>0.14</td>
</tr>
<tr>
<td>P</td>
<td>0.40</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Table C2

Descriptive statistics for COP-Y average (cm) in the stable bilateral eyes closed (BLEC) for barefoot (BF), Vibram™ Bikila, Vibram™ Trek Ascent according to the foot types neutral (N), supinated (S) and pronated (P)

<table>
<thead>
<tr>
<th>Stable BLEC</th>
<th>COP-Y average (cm)</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF</td>
<td>N</td>
<td>4.11</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>3.26</td>
<td>1.46</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>3.69</td>
<td>2.62</td>
</tr>
<tr>
<td>VB</td>
<td>N</td>
<td>4.93</td>
<td>1.91</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>3.63</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>5.00</td>
<td>2.34</td>
</tr>
<tr>
<td>VT</td>
<td>N</td>
<td>3.38</td>
<td>1.42</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>3.80</td>
<td>1.79</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>3.92</td>
<td>3.10</td>
</tr>
</tbody>
</table>
Table C3

*Descriptive statistics for average displacement along X (cm) in the stable unilateral eyes closed (ULEC) for barefoot (BF), Vibram™ Bikila, Vibram™ Trek Ascent according to the foot types neutral (N), supinated (S) and pronated (P)*

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td></td>
</tr>
<tr>
<td>Stable ULEC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average displacement along X (cm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>0.77</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>0.78</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>0.82</td>
<td>0.17</td>
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</tr>
<tr>
<td></td>
<td>VB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>0.89</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>0.90</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>0.89</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td></td>
<td>VT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>0.86</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>0.89</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>0.86</td>
<td>0.24</td>
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</tr>
</tbody>
</table>
Table C4

Descriptive statistics for 95% Ellipse Area (cm.cm) in the stable unilateral eyes closed (ULEC) for barefoot (BF), Vibram™ Bikila, Vibram™ Trek Ascent according to the foot types neutral (N), supinated (S) and pronated (P)

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BF</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>19.12</td>
<td>5.47</td>
</tr>
<tr>
<td>S</td>
<td>18.01</td>
<td>8.05</td>
</tr>
<tr>
<td>P</td>
<td>24.57</td>
<td>7.91</td>
</tr>
<tr>
<td><strong>VB</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>25.43</td>
<td>4.29</td>
</tr>
<tr>
<td>S</td>
<td>27.19</td>
<td>8.93</td>
</tr>
<tr>
<td>P</td>
<td>25.26</td>
<td>8.51</td>
</tr>
<tr>
<td><strong>VT</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>21.53</td>
<td>4.43</td>
</tr>
<tr>
<td>S</td>
<td>25.23</td>
<td>8.69</td>
</tr>
<tr>
<td>P</td>
<td>28.28</td>
<td>14.64</td>
</tr>
</tbody>
</table>
Table C5

*Descriptive statistics for COP-Y average (cm) in the unstable bilateral eyes open (BLEO) for barefoot (BF), Vibram™ Bikila, Vibram™ Trek Ascent according to the foot types neutral (N), supinated (S) and pronated (P)*

<table>
<thead>
<tr>
<th>Unstable BLEO COP-Y average (cm)</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF N</td>
<td>3.00</td>
<td>1.50</td>
</tr>
<tr>
<td>S</td>
<td>2.69</td>
<td>1.41</td>
</tr>
<tr>
<td>P</td>
<td>2.71</td>
<td>1.65</td>
</tr>
<tr>
<td>VB N</td>
<td>3.58</td>
<td>1.43</td>
</tr>
<tr>
<td>S</td>
<td>3.62</td>
<td>1.55</td>
</tr>
<tr>
<td>P</td>
<td>4.26</td>
<td>1.44</td>
</tr>
<tr>
<td>VT N</td>
<td>2.75</td>
<td>1.03</td>
</tr>
<tr>
<td>S</td>
<td>4.06</td>
<td>1.35</td>
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<tr>
<td>P</td>
<td>2.99</td>
<td>2.16</td>
</tr>
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</table>
Table C6

Descriptive statistics for COP-Y average (cm) in the unstable bilateral eyes closed (BLEC) for barefoot (BF), Vibram™ Bikila, Vibram™ Trek Ascent according to the foot types neutral (N), supinated (S) and pronated (P)

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF</td>
<td>N</td>
<td>2.50</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>2.49</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>2.45</td>
</tr>
<tr>
<td>VB</td>
<td>N</td>
<td>3.54</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>3.28</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>3.58</td>
</tr>
<tr>
<td>VT</td>
<td>N</td>
<td>3.61</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>3.61</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>4.24</td>
</tr>
</tbody>
</table>
Table C7

Descriptive statistics for average displacement along Y (cm) in the unstable unilateral eyes opened (ULEO) for barefoot (BF), Vibram™ Bikila, Vibram™ Trek Ascent according to the foot types neutral (N), supinated (S) and pronated (P)

<table>
<thead>
<tr>
<th></th>
<th>Unstable ULEO Average displacement along Y (cm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>BF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>1.02</td>
<td>0.27</td>
</tr>
<tr>
<td>S</td>
<td>0.85</td>
<td>0.21</td>
</tr>
<tr>
<td>P</td>
<td>0.90</td>
<td>0.27</td>
</tr>
<tr>
<td>VB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>0.81</td>
<td>0.10</td>
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<tr>
<td>S</td>
<td>0.79</td>
<td>0.19</td>
</tr>
<tr>
<td>P</td>
<td>0.79</td>
<td>0.18</td>
</tr>
<tr>
<td>VT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>0.83</td>
<td>0.21</td>
</tr>
<tr>
<td>S</td>
<td>0.75</td>
<td>0.13</td>
</tr>
<tr>
<td>P</td>
<td>0.78</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Table C8

*Descriptive statistics for 95% Ellipse Area (cm.cm) in the unstable unilateral eyes opened (ULEO) for barefoot (BF), Vibram™ Bikila, Vibram™ Trek Ascent according to the foot types neutral (N), supinated (S) and pronated (P)*

<table>
<thead>
<tr>
<th>Unstable ULEO</th>
<th>95% Ellipse Area (cm.cm)</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF</td>
<td>N</td>
<td>20.16</td>
<td>8.30</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>17.05</td>
<td>6.27</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>16.78</td>
<td>6.60</td>
</tr>
<tr>
<td>VB</td>
<td>N</td>
<td>15.78</td>
<td>1.58</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>16.32</td>
<td>4.85</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>15.34</td>
<td>4.52</td>
</tr>
<tr>
<td>VT</td>
<td>N</td>
<td>16.33</td>
<td>5.71</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>14.76</td>
<td>4.25</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>14.48</td>
<td>4.45</td>
</tr>
</tbody>
</table>
Table C9

Descriptive statistics for average displacement along Y (cm) in the unstable unilateral eyes closed (ULEC) for barefoot (BF), Vibram™ Bikila, Vibram™ Trek Ascent according to the foot types neutral (N), supinated (S) and pronated (P)

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF</td>
<td>1.33</td>
<td>0.19</td>
</tr>
<tr>
<td>S</td>
<td>1.31</td>
<td>0.32</td>
</tr>
<tr>
<td>P</td>
<td>1.49</td>
<td>0.45</td>
</tr>
<tr>
<td>VB</td>
<td>1.51</td>
<td>0.36</td>
</tr>
<tr>
<td>S</td>
<td>1.50</td>
<td>0.35</td>
</tr>
<tr>
<td>P</td>
<td>1.74</td>
<td>0.41</td>
</tr>
<tr>
<td>VT</td>
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<td>0.39</td>
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<tr>
<td>S</td>
<td>1.35</td>
<td>0.21</td>
</tr>
<tr>
<td>P</td>
<td>1.68</td>
<td>0.34</td>
</tr>
</tbody>
</table>
Table C10

Descriptive statistics for 95% Ellipse Area (cm.cm) in the unstable unilateral eyes closed (ULEC) for barefoot (BF), Vibram™ Bikila, Vibram™ Trek Ascent according to the foot types neutral (N), supinated (S) and pronated (P)

<table>
<thead>
<tr>
<th>Unstable ULEC</th>
<th>95% Ellipse Area (cm.cm)</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF</td>
<td>N</td>
<td>37.08</td>
<td>6.66</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>35.69</td>
<td>12.18</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>42.26</td>
<td>16.94</td>
</tr>
<tr>
<td>VB</td>
<td>N</td>
<td>44.25</td>
<td>14.49</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>45.42</td>
<td>14.28</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>49.96</td>
<td>18.16</td>
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<td>N</td>
<td>48.26</td>
<td>13.72</td>
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<td>37.87</td>
<td>8.73</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>50.22</td>
<td>17.28</td>
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</tbody>
</table>