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The Impact of Shod Versus Unshod Walking on Center of Pressure Variability

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THE IMPACT OF SHOD VERSUS UNSHOD WALKING ON CENTER OF PRESSURE VARIABILITY

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ABSTRACT

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The purpose of the present investigation was to examine the influence of footwear on walking stability. Twenty healthy women walked at 1.3 m/s on an instrumented treadmill. One hundred steps (50-right, 50-left) were analyzed from two walking conditions (shod, unshod). The variability of the center of pressure (COP) for each step was calculated for quadrants of the contact period. Significant differences in variability were seen between shod and unshod conditions in all quadrants as well as differences between left and right feet in quadrants one and four. Restricted foot motion while shod may explain the differences seen in COP variability. This suggests footwear may provide a more stable walking base for “at-risk” populations from which they are less likely to fall than when barefoot.

ACKNOWLEDGEMENTS

I dedicate this thesis to my amazing wife Katelyn without whom this thesis and the proceeding two years of study would not have been possible. Thank you for your encouragement and support and thank you for pulling me back every time my stress pushed me towards the precipice of insanity. Your contribution was irreplaceable, I love you.

A thank you to Dr. Heise and Otto Buccholz for answering my many questions and for your ever-continuing patience and finally, thank you to my family. Not because you contributed to this thesis but you did provide genetic material, raise, fund and provide shelter for me so thank you for that and setting an example of achieving academic excellence. Except you Jake and Genevieve, I think you made me dumber.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Introduction

In 2015, over 60 million Americans were rushed to the emergency room, accumulating more than $50 billion in medical costs due to fall related injuries (Florence et al., 2018). Falls, defined as “a sudden, unintentional change in position coming to rest on the ground or other lower level” (Desforges, Tinetti, & Speechley, 1989) are the leading cause of fatal and non-fatal injuries among the elderly (Falls in the Elderly Statistics, NCOA, 2016). In response to repeated annual statistics such as these, stability, as it pertains to falls, is a saturated topic in the literature. Despite this saturation, the vast majority of studies on stability examine static stability, a task which only accounts for a small percentage of most people’s daily activity and neglects the need for stability during the over five thousand steps taken by the average American each day (Bassett, Wyatt, Thompson, Peters, & Hill, 2010).

Up to 70% of elderly falls occur while walking, among other common tasks, making the study of dynamic stability of high importance (Soriano, DeCherrie, & Thomas, 2007). Within the study of dynamic stability, center of pressure is a common measure especially in terms of its variability.

Center of pressure (COP) is defined as “a point on a surface through which the resultant force due to pressure passes” (Centre of pressure, Definition of centre of pressure in English by Oxford Dictionaries, 2019). Measuring COP trajectory has been used in biomechanics as a means of measuring postural stability both during static and dynamic tasks. During gait, dynamic stability is measured by mapping the COP trajectory as it passes through the foot, the trajectory, when compared to a relative norm, indicating discrepancies in an individual's gait making them potentially more likely to fall. In part, one such discrepancy is the step-to-step variability with which the COP crosses under the foot.

Variability is present in numerous forms when it comes to human physiology and biomechanics. In certain instances, variability is a sign of good health, as is the case in heart rate variability. A healthy heart has a high degree of variability, which, if lacking, has been linked with severe coronary artery disease, congestive heart failure and diabetic neuropathy (Kleiger, Miller, Bigger, & Moss, 1987). However, high degrees of measured variability in other metrics, such as gait, have been linked with negative outcomes, such as an increased risk of falls, especially in growing "at risk" populations.

The elderly, classified as individuals over 60 years of age, is a demographic expected to double by 2050 ("Ageing | United Nations," n.d.). This population currently experiences over 800,000 hospitalizations each year due to fall related injuries, at an average cost of $30,000 per injury (Florence et al., 2018). Further underscoring the importance of dynamic stability for the elderly, Gribbin, Hubbard, Smith, Gladman and Lewis (2009) determined falls in the elderly to be highly correlated with risk of mortality. Increases in gait variability, resulting in decreased dynamic stability of the elderly can be seen in multiple gait metrics and is influenced by multiple conditions experienced daily making them the first "at risk" population to be discussed.

In 2005 there were nearly 2 million Americans living with a limb amputation (Ziegler-Graham, MacKenzie, Ephraim, Travison, & Brookmeyer, 2008) with approximately 185,000 limb amputations occurring each year (Dillingham, Pezzin, & Mackenzie, 2002). Of those amputees, 50% fall within the first year post amputation and 40% of those result in injury (Felcher et al., 2015). Of those amputees that fall, 33% will fall again (Dyer, Bouman, Davey, & Ismond, 2008). Therefore, amputees are the second "at risk" population for falls and in need of examination to determine if their dynamic stability is compromised by increased gait variability.

The final "at risk" population for falls, are a group of individuals afflicted with diseases and health conditions such as stroke, arthritis and Parkinson's disease. Prevalence of each of these diseases differ, with the likelihood of developing knee or hip osteoarthritis standing at 45% and 25% respectively (Murphy et al., 2008), the risk of having a stroke standing at 20% for women and 17% for men ("Types of stroke | Ischaemic, Haemorrhagic and TIA's | Stroke Association," 2018), and the risk of developing Parkinson's disease increasing with age from less than 1% for individuals between ages 40 and 49 to over 1% in individuals between ages 70 and 79 (Pringsheim, Jette, Frolkis, & Steeves, 2014). What they have in common is with diagnosis comes an increased risk of falls. Once afflicted with arthritis, victims are 2.5 times more likely to have 2 or more falls than those without (Barbour et al., 2014). In a study by Simpson, Miller and Eng (2011) stroke victims were found to fall at a rate 1.77 times that of the control group and in a review paper 60.5% of participants afflicted with Parkinson's disease from 22 studies reported falling with 39% reporting recurrent falls (Allen, Schwarzel, & Canning, 2013; Simpson, Miller, & Eng, 2011). Studies have suggested a reason for this prevalence of falls may be in part due to variability of gait. A commonality linking these three “at risk” groups and their risk of falls, in part, is the role with which footwear plays.

Shod, the state of wearing footwear, and unshod, the state of being barefoot or in foot coverings closely mimicking barefoot conditions, are states often compared and contrasted. With annual shoe sales topping $81 billion in the US understanding their impact on gait is of much importance (“FDRA | Footwear Retail,” n.d.).

In 1999, Munro and Steele conducted a survey and found among the elderly, defined as 65 years old and above, the most common footwear worn around the house was either barefoot or slippers (Munro & Steele, 1999). Similar results were found in Parkinson’s and stroke patients by Bowen et al. (2016). These findings are troublesome when taken into context with the findings of Kelsey et al. (2010), and Koepsell et al., (2004) both of whom found significant increases in risk of falling when in bare feet, socks or slippers. In the 2010 study, Kelsey et al. reported 51.9% of reported falls occurred when barefoot, wearing socks alone or slippers, a rate significantly higher than that seen when wearing other forms of footwear.

“At risk” populations suffer from significantly higher rates of falls then the general public, incurring high medical expenses and putting them at increased risk for future falls and injury. Variability of gait and footwear are two factors known to influence this risk. Using a common measure of dynamic stability, COP, this thesis will seek to examine the effect of footwear on that variability. Therefore, this review will examine literature analyzing variability, center of pressure and shod vs unshod conditions.

Literature Review

Variability

Elderly.

Spatiotemporal variables. Aging, in its unadulterated form, is known to have an impact on gait spatiotemporal variables such as reduced velocity, shorter steps, slower cadence , less vertical displacement of center of mass, and longer double support time (Maki, 1997). Increases in gait variability, which has been identified as a contributor to risk of falls (Hausdorff, Rios, & Edelberg, 2001) however, may not be a result of the natural aging process**.** Gabell and Nayak (1984) examined the variability of the spatiotemporal variables step length, stride time, stride width and double support time in two groups of participants, the first being of ages 21 to 47 and the second being of ages 66 to 84. The results of the study indicate no significant gender or age-related differences between participants for any variable prompting authors to propose the changes in gait variability, previously thought to be associated with aging, to be the result of a pathology, not aging itself. This hypothesis gains merit when examining studies that specifically compare elderly individuals with and without a history of falls.

In studies by Mbourou, Lajoie, and Teasdale (2003) and Brach, Berlin, VanSwearingen, Newman and Studenski (2005), the variability of gait spatiotemporal measures of participants with and without a history of falls were compared. Mbourou et al. (2003) compared three groups, young, older individuals without a history of falls, and older individuals with a history of falls, in terms of their variability of first step length and first double support period when initiating gait. Elderly individuals with a history of falls demonstrated significantly greater variability in first step length (125 vs 57 and 56 mm, respectively) and first double support time and compared to the young and elderly non-fallers whose results were not significantly different. Brach et al. (2005) found no differences between groups of fallers and non-fallers when comparing variability, using a coefficient of variation, of step length (6.5% vs. 6.3%), stance time (5.2% vs. 4.9%), and step time (4.7% vs. 4.7%) however individuals who had fallen in the last 12 months exhibited what authors described as extreme step width variability (21.8% vs. 17.8%). While these studies suggest that changes in the variability of gait may be due to more than natural aging, the results of Mills, Barrett, and Morrison (2008) suggest that this might not be an accurate blanket conclusion.

In a study comparing the variability of minimum toe clearance of two groups made up of 10 young and 10 elderly participants respectively, Mills et al. (2008) found the elderly group exhibited greater inter-participant minimum toe clearance variability (effect size = 0.96) despite a requirement of participation in the study being a lack of falls in the previous two years. This suggests that although the variability of some spatiotemporal gait variables may increase more due to pathologies than the aging process, this may not hold true for all variables.

Daily gait perturbances. Worth considering in the discussion of gait variability as it pertains to falls, especially in the elderly, is the effect of daily gait perturbances. Studies by Almarwani, VanSwearingen, Perera, and Sparto (2016), Richardson, Thies, DeMott and Ashton-Miller (2004), and Hollman, Kovash, Kubik, and Linbo (2007) examined the effects of three perturbances, gait speed, uneven surfaces navigation and dual task walking, respectively, on gait variability. What was found was, with each perturbance, gait variability, more specifically gait variability of spatiotemporal variables such as double support time, stance time, swing time, step time, stride width and stride velocity and increased more significantly in elderly groups than in younger control subjects. For instance, the stride-to-stride variability in gait velocity increased from a 3.0% coefficient of variation (CV) to 3.5% in the younger control subjects and from 8.5% CV to 14.5% CV in the elderly group (Hollman et al., 2007). This suggests that daily gait perturbances may be partially to blame for the elderly's' increased risk of falling.

Amputees.

Spatiotemporal variables. Vanicek, Strike, McNaughton, and Polman (2009) examined two groups of trans tibial amputees, those with a fall within the previous 9-months leading up to testing and those without. Among the multitude of differences found between groups, the group with a history of falls was found to have significantly greater variability of swing time duration of the intact limb ($p = 0.03$).

Kinetic variables. Ground reaction force variability of two different prosthetic feet was analyzed by Svoboda, Janura, Cabell, & Elfmark (2012). They found high levels of variability, meaning coefficients of variation between 10-20%, for both anterior-posterior and mediolateral ground reaction forces. These differences in variability were suggested to be the result of prosthetic foot construction.

Kinematic variables. In a study examining amputee walking on irregular surfaces and dual task walking, Lamoth, Ainsworth, Polomski, and Houdijk (2010) found amputees demonstrated greater variability in mediolateral trunk accelerations. For instance, while walking indoors amputee's CV was calculated to be 0.21% versus 0.14% in healthy controls. When paired with the additional findings that amputees also demonstrated less regular, locally stable acceleration patterns, researchers concluded this to be evidence of impaired balance control in amputees.

Disease states.

Osteoarthritis. Matsumoto et al. (2015) examined the relationship between knee osteoarthritis, gait variability and falls in 91 participants using a triaxial accelerometer placed at the L3 level of the spine. What they found were significant relationships between the diagnosis of knee osteoarthritis ($p = 0.043$), increased gait variability, as measured using the accelerometer, ($p = 0.039$) and a history of falls.

Stroke. A 2009 study by Balasubramanian, Neptune, and Kautz (2009) examined the effect of a stroke on gait variability in 94 participants, 69 stroke victims at least six months removed from the event and 22 age-matched controls. They found the stroke victims demonstrated increased pre-swing variability, stride time variability, and reduced stride width variability.

Parkinson's disease. Dopaminergic pathways in the brain have been shown to play a role in impaired gait rhythmicity in Parkinson's disease. (Schaafsma et al., 2003) To test this premise as it relates to gait variability, Bryant et al. (2011) tested Parkinson's patients on and off dopaminergic medication. They found after a treatment of dopaminergic medication, participants demonstrated significantly decreased levels of variability of step time, double support time, stride length and stride velocity ($p = 0.037$, $p = 0.037$, $p = 0.022$, $p = 0.043$, respectively).

Center of Pressure

Elderly. It should come as no surprise that among age-related changes in gait, come changes in center of pressure in the elderly. In studies comparing experimental groups of young and old, Chiu, Wu, Chang and Wu (2013) and Sole, Pataky, Sole, Hale and Milosavljevic (2017) found the elderly participants demonstrated a significantly more medial COP curve and faster COP velocity during the initial contact phase, a more pronated mid foot posture, as indicated by COP location, and a slower COP velocity during midstance and a more lateral COP placement in late stance. The true cause of the slower COP velocity during midstance is unclear and remains up for debate.

The inclination angle, an angle between the vertical axis and a theoretical line connecting the COP and an individual's center of mass, "quantifies ... a person's balance maintenance during locomotion" is a useful tool when determining risk of falls. In a comparison of participants with and without a history of falls, inclination angles were found to be significantly greater in the medial direction but smaller in the anterior direction among fallers when compared to their healthy control counterparts (Lee & Chou, 2006). In a study using inclination angles to determine the effect of incline walking, a task more challenging to the locomotor system, the elderly experimental group was shown to have greater inclination angle range of motion in the sagittal plane, increase rate of change of inclination angle at heel strike, during single and double limb support in the sagittal plane and increased rate of change of inclination angle at heel strike in the frontal plane (Hong et al., 2015).

Osteoarthritis. Osteoarthritis can occur in multiple lower body joints such as the hip, knee and metatarsophalangeal joints impacting COP trajectories during gait. Lidtke, Muehleman, Kwasny, and Block (2010), examined 25 participants with knee osteoarthritis and 25 healthy control participants. The group suffering from knee osteoarthritis demonstrated significantly higher lateral loading of the foot during contact and midstance when compared to the controls ($p < 0.001$). When examining a group of individuals with osteoarthritis of the first metatarsophalangeal joint, Menz, Auhl, Tan, Buldt, and Munteanu (2018) found the pre-swing phase of gait to be significantly impacted with a slower maximum COP velocity (0.78 ± 0.19 vs 1.13 ± 0.36 m/sec) and a significantly higher average and maximum medial-lateral force indices.

Amputee. Amputee populations produce a challenge when studying COP as amputee gait often presents an asymmetrical pattern, both sides of which must be compared to a control subjects gait (Schmid, Beltrami, Zambarbieri, & Verni, 2005). In a direct comparison of COP in transfemoral amputees and healthy control subjects, it was found the prosthetic limb demonstrated a greater amount of time spent in double support (16.4% of stance vs 13.6%) and with the COP in the heel and midfoot regions of the foot (25.8% of stance vs 13.5%). In the intact limb, amputees demonstrated a longer stance phase and a greater duration of time spent in the forefoot (Schmid et al., 2005). To complicate the analysis of amputees' gait further, different prosthetics may have different effects on COP.

De Asha, Johnson, Munjal, Kulkarni and Buckley (2013) studied the effect of two different prosthetic ankles on COP in 20 active unilateral trans tibial amputees. The ankles differed in that one had an elastic articulating joint whereas the other was a hydraulic attachment. It was found that the hydraulic ankle was superior, reducing the magnitude of posterior COP displacement and COP velocity variability across single support. Furthermore, it increased mean forward angular velocity of the shank during early stance and increased the amputees preferred walking speed.(De Asha, Johnson, Munjal, Kulkarni, & Buckley, 2013)

Center of Pressure and Variability

To this point, it has been covered that the analysis of COP trajectory is an accepted measure of stability in the literature and that variability in gait has been linked to falls in "at risk" populations. To analyze the intricacies of the relationships between COP, variability and falls, two papers deserve an in-depth examination.

Variability of center of pressure movement during gait in young and middle-aged women. In 2014 the journal Gait and Posture published a study conducted by Bizovska, Svoboda, Kutilek, Janura, Gaba, and Kovacikova comparing the variability of center of pressure in two populations, young, consisting of participants of an average age of 22.2 years, and an elder group, consisting of participants of an average age of 56.6 years.(Bizovska et al., 2014) Participants were tasked with 8 trials of barefoot walking down an 8m walkway at a self-selected pace over a Kistler force plate. Vertical ground reaction forces and COP data were collected for comparison. They divided the stance phase of gait into four quadrants based on the vertical ground reaction force of each step. Quadrant one spanned from heel contact through impact peak maxima, quadrant two spanned impact peak maxima through impact trough minima, quadrant three spanned from impact peak-trough minima through propulsive peak maxima and quadrant four spanned from propulsive peak maxima through toe off. Within each of these quadrants variability of COP was quantified in the form of the standard deviation of the 5 trials kept for each participant, the first three having been removed to account for familiarization of task. The results of the study were that the elder group demonstrated significantly higher COP movement variability in the medial-lateral (M-L) direction and total COP displacement in quadrant one, greater variability in the M-L direction in quadrant two, and greater variability in both M-L and anterior-posterior (A-P) directions as well as total COP displacement in quadrant four.

While the results of this study certainly suggest an impact of age, a potential indicator of risk of falls, on COP variability the next study must be relied upon to connect COP, variability, and risk of falls.

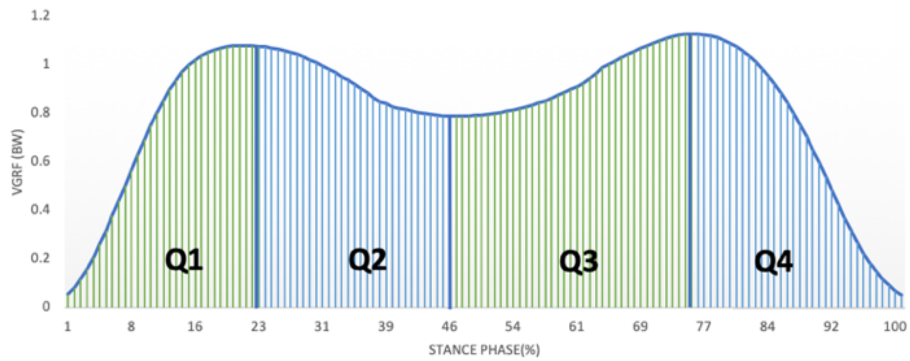

Figure 1.1: COP quadrants based on the peaks and trough of associated vGRF.

Variability of center of pressure displacements during gait in fallers and nonfallers: A 6-month prospective study. In a follow-up study involving the same first and second authors of the previous paper, the relationship between variability of COP and falls was examined.(Svoboda, Bizovska, Janura, & Kubonova, 2016) Participants in the study were made up of 125 elderly individuals of average age 70.6 years. Inclusion criteria included the ability to walk unassisted and to stand unassisted while doing common daily tasks. Participants performed 5 barefoot walking trials over a 10m walkway outfitted with two force plates at three speeds, self-selected, predetermined and fast. For the six months following data collection, incidences of falls were collected from participants via the phone every two weeks. After application of the Holm-Bonferroni method for multiple comparisons, there were no significant correlations between variables. However, authors noted variability of COP in the M-L direction during the pre-swing phase of gait was extremely close to achieving significance in identifying fallers and non-fallers (Svoboda et al., 2016).

Shod vs. Unshod

Kinetic variables. Putting on a pair of shoes alters the forces experienced at each joint. The hip experiences greater levels of energy generation and absorption along with greater flexion and extension moments (Keenan, Franz, Dicharry, Croce, & Kerrigan, 2011; Kung, Fink, Hume, & Shultz, 2015). At the knee, there is as much as a 5% increase in resultant force, a 12% increase in internal adduction moment and a 5% increase of forces on the medial compartment (Kutzner et al., 2013). Not to be left out, the ankle experiences greater maximal dorsiflexion moments and a greater dorsiflexion impulse. When the shoes come off there is an increase in hip flexor impulse along with increased subtalar inverter moments and increased energy generation by the ankle plantar flexors and inverters (Kung et al., 2015).

Kinematic variables. In shod conditions during walking gait there is greater maximal hip flexion, knee flexion and peak ankle dorsiflexion.(Kung et al., 2015) Ankle eversion is slower, smaller, and occurs later, 1.2° at 11.5% of stance as opposed to 8.7° at 27.8% in unshod conditions.(Campbell, Wilson, LaPrade, & Clanton, 2016; Morio, Lake, Gueguen, Rao, & Baly, 2009) In shod conditions rotation about the sagittal axis and adduction ranges of motion seen in unshod conditions appear to be restricted (Morio et al., 2009).

Spatiotemporal variables. When comparing shod and unshod conditions there are a number of spatiotemporal variable differences. On average, while shod, step length increases by 6.5% potentially increasing walking speed by as much as 8 cm/s (Keenan et al., 2011; Lythgo, Wilson, & Galea, 2009). Similarly, a shod condition results in an increased base of support, 0.5 cm, double support and stance time, by 1.6% and 0.8% respectively, while single support time decreases by 0.8%. Finally, cadence is decreased by 3.9 steps per minute on average (Lythgo et al., 2009).

Summary

Among the greater population are multiple groups of individuals at increased risk of falls, resulting in severe injuries and requiring significant medical treatment. The severe consequences of such falls make the lack of research on dynamic stability unacceptable and in need of correction. Three areas of research that may shed light on the cause of this risk include center of pressure, movement variability and shod vs unshod foot conditions. Each of these areas have been found by previous research to individually be related to and impact an individual's risk of falls as they alter kinematic, kinetic and spatiotemporal variables. These impacts include phenomena such as increasing swing time variability, increased deviation in COP trajectory and decreased rates of foot motion. It is for this reason, and a lack a research doing so, that the relationship between these variables was examined by this thesis seeking to answer the following question. What is the effect of shod vs unshod foot conditions on the variability of center of pressure during treadmill walking in a health population?

CHAPTER II

METHODS

Data Collection

Twenty healthy, non-smoking, physically-active adult females, ages 18 to 30 yr, were recruited for the study. A "physically-active individual" was defined in accordance with the American College of Sports Medicine as an individual who participates in moderately intense physical activity for 30 minutes per day on three or more days per week (Pate, Neill, Dowda, Saunders, & Brown, 2009). Additionally, participants had to be free from lower extremity injury for the previous six months.

Prior to study participation, volunteers received a written informed consent form and met with the principal investigator (PI) or research assistants who explained the purpose, procedure and potential risks associated with participation. The principal investigator assessed each volunteer's level of understanding verbally and collected a signed consent form from each participant before testing commenced. The study was approved by the local institutional review board.

To control for footwear in the shod condition, participants were provided shoes (Brooks Launch 5), additionally socks and form-fitting clothing were also supplied. Height and weight were recorded prior to two five-minute acclimation periods, shod and unshod, during which participants walked at a pace of 1.3 m/s. Ten-minute rest periods were taken between each trial.

Test trials, of which there were two, consisted of 10 minutes of walking during which kinematic (200 Hz) and kinetic (2000 Hz) data were collected between the 8th and 9th minutes using an AMTI (AMTI Force and Motion, Watertown, MA), force plate equipped, dual belt treadmill and a Vicon motion capture system (Vicon, Centennial, CO). The order of the footwear conditions was randomized. After all testing was completed the markers were removed and the participant changed back into their personal clothing.

Data Analysis

Visual 3D software (V3D) (C-motion, Inc., Germantown, MD) was used to process the kinetic and kinematic data. A 4th order, digital Butterworth filter was applied with cutoff frequencies of 6 Hz and 10 Hz for kinematic and kinetic data respectively. A threshold equal to 5% of a participant's body weight was applied to the vertical ground reaction force in order to identify foot contact events. Heel-on and toe-off for 100-foot contacts (50-left, 50-right) collected over 60 seconds were automatically identified by V3D**,** defined as the first and final frames the vertical GRF vector surpassed the 5% force threshold. In addition, automatic gait events, as assigned by V3D, were visually corrected by a single researcher to align with force vector appearance and disappearance. Irregular foot contacts, identified by examining the vertical ground reaction force, were marked for exclusion during exportation from V3D. Center of pressure was calculated using the measured moments, known origin of the force plate, and ground reaction forces. COP data were then processing using a custom Matlab (Mathworks, Natick, MA) software that analyzed the variability of COP displacement in the medial-lateral (ML) and anterior-posterior (AP) direction as well as a total displacement value following the methodology as describe by Bizovska et al. (2014) (Table 1).

Table 2.1

Description of observed variables.

Displacement	Description	Computation
ML	Medial-Lateral Displacement	$D_{ML} = \lvert X_i - X_{i-1} \rvert$
AP	Anterior-Posterior Displacement	$D_{ML} = \lvert Y_i - Y_{i-1} \rvert$
Total	Total Displacement	$D_{Total} = \sqrt{D_{ML}^2 + D_{AP}^2}$

*Equations sourced from Bizovska et al. (2014)

Statistical Analysis

For each quadrant, the mean values of the standard deviations in the ML and AP directions as well as the mean of the standard deviation of the total displacement were used for further analyses. A single MANOVA was used to determine effects of footwear (within-subject independent variable) and limb (between-subject independent variable) for each quadrant with the probability of a Type I error set at 0.05. A total of 12 dependent variables were used in the MANOVA (4 quadrants, 3 directional measures). Statistical analysis was performed using SPSS software (IBM, Armonk, NY, USA).

CHAPTER III

JOURNAL MANUSCRIPT

THE IMPACT OF SHOD VS UNSHOD WALKING ON CENTER OF PRESSURE VARIABILITY

Contribution of Authors and Co-Authors

Author: Zachary Barrons

Contributions: Primary researcher when collecting data, analysis and writing thesis.

Author: Otto Buchholz

Contribution: Provided technical support and aide during data collection and analysis.

Author: Gary D. Heise

Contribution: Provided support in development, analysis and writing of thesis.

Introduction

With 60 million Americans rushed to the ER with fall related injuries in 2015 alone, the saturation of research on falls is well substantiated (Florence et al., 2018). Numerous explanations have been given for the high rate of falls including environmental factors, amputations, diseases and advanced age; however, mounting evidence suggests there may be a commonality underlying these explanations, mainly movement variability (Allen, Schwarzel, & Canning, 2013; Felcher et al., 2015; Rubenstein & Josephson, 2002; Talbot, Musiol, Witham, & Metter, 2005).

Variability is present in numerous forms in human physiology and biomechanics, for example heart rate variability. In certain instances, as is the case with heart rate, variability is a sign of good health, a healthy heart has a high degree of variability, which, if lacking, has been linked with negative outcomes such as severe coronary artery disease, congestive heart failure and diabetic neuropathy (Kleiger, Miller, Bigger, & Moss, 1987). However, high degrees of measured variability in other metrics, such as gait, have been linked with negative outcomes, such as an increased risk of falls (Barak, Wagenaar, & Holt, 2006; Hausdorff, Edelberg, Mitchell, Goldberger, & Wei, 1997).

In comparisons of elderly participants, those with a history of falls exhibit significantly greater variability in gait measures such as first step length, stride length and stride time (Hausdorff, Rios, & Edelberg, 2001; Maki, 1997; Mbourou, Lajoie, & Teasdale, 2003). The strongest research argument was made by Hausdorff et al. (2001) in a yearlong prospective study. They found gait variability measures to be effective predictors of elderly falls in the 12 months following evaluation (Hausdorff et al., 2001). In addition, an increase in gait variability in those with a history of falls has also been found in amputee populations and those with certain medical conditions (e.g., strokes, Parkinson's disease, and osteoarthritis)(Balasubramanian, Neptune, & Kautz, 2009; Bryant et al., 2011; Lamoth, Ainsworth, Polomski, & Houdijk, 2010; Matsumoto et al., 2015; Svoboda, Janura, Cabell, & Elfmark, 2012; Vanicek, Strike, McNaughton, & Polman, 2009).

With up to 70% of elderly falls occurring while walking (Kelsey et al., 2010), among other common daily tasks, gait variability is the suspected cause, a premise investigated by Bizovska et al. (2014). To do so, a methodology was developed to analyze the center of pressure (COP) during the stance phase of walking. COP analysis is most commonly used under static conditions to assess a person's postural stability (Melzer, Benjuya, & Kaplanski, 2004; Merlo et al., 2012). Bizovska et al. (2014) presented an in-depth analysis of differences in gait COP variability between younger (22.16±1.80 years) and elder (56.63±4.85 years) participant groups. They divided the stance phase COP of individual steps into quadrants (Q1-Q4) based on the peaks and trough of associated vertical ground reaction forces (Figure 1). The results of their study supported a previous finding that elder adults displayed more variable, COP trajectories (Svoboda, Bizovska, Janura, & Kubonova, 2016).

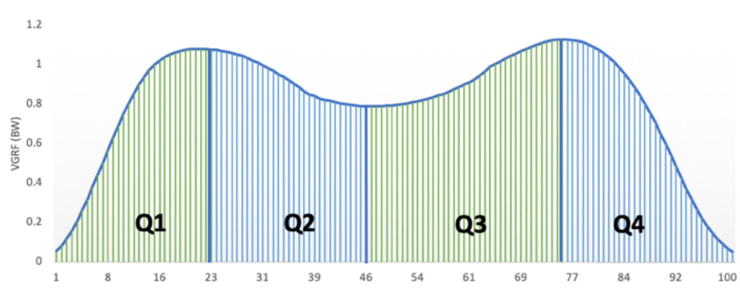

Figure 3.1: COP quadrants based on the peaks and trough of associated vGRF.

The aforementioned research identifying gait variability as a potential contributor to the high annual incidence of falls has, up to this point, omitted the influence of footwear. As reported by Munro & Steele (1999) the most common footwear worn around the home by the elderly are slippers followed by barefoot. While predictable when taking comfort and convenience into consideration, the lack of footwear worn around the home is troublesome when taken in context with research by Kelsey et al. (2010), and Menz, Morris and Lord (2006). Kelsey et al. (2010) followed 765 participants for a median of 27.5 months and found the majority of falls in that timespan occurred in the home when barefoot or in barefoot like conditions (i.e., socks and slippers). Furthermore, they determined the odds of sustaining a serious fall related injury when barefoot were significantly higher (2.27x). Menz et al. (2006) found individuals who fell indoors were more likely to have gone barefoot and/or shod in socks, the correlation so strong they went so far as to suggest elderly individuals deemed a fall risk should wear shoes indoors as a fall prevention measure (Menz, Morris, & Lord, 2006).

In an effort to continue unraveling the high rates of elderly falls by establishing normative data for future comparisons, this study will build upon the results and methodology developed by Bizovska et al. (2014) whilst simultaneously examining the impact of footwear and its role in the problem. Therefore, the purpose of this research was to study the influence of footwear on dynamic walking gait stability by examining the variability of COP trajectories. It was hypothesized that footwear would reduce COP variability in both ML and AP direction when compared to unshod or barefoot walking.

Materials and Methods

Subjects and Experimental Set Up

Twenty healthy, non-smoking, physically-active adult females, ages 18 to 30 yr, were recruited for the study. A "physically-active individual" was defined in accordance with the American College of Sports Medicine as an individual who participates in moderately intense physical activity for 30 minutes per day on three or more days per week (Pate, Neill, Dowda, Saunders, & Brown, 2009). Additionally, participants had to be free from lower extremity injury for the previous six months.

Prior to study participation, volunteers received a written informed consent form and met with the principal investigator (PI) or research assistants who explained the purpose, procedure and potential risks associated with participation. The principal investigator assessed each volunteer's level of understanding verbally and collected a signed consent form from each participant before testing commenced. The study was approved by the local institutional review board.

To control for footwear in the shod condition, participants were provided shoes (Brooks Launch 5), additionally socks and form-fitting clothing were also supplied. Height and weight were recorded prior to two five-minute acclimation periods, shod and unshod, during which participants walked at a pace of 1.3 m/s. Ten-minute rest periods were taken between each

Test trials, of which there were two, consisted of 10 minutes of walking during which kinematic (200 Hz) and kinetic (2000 Hz) data were collected between the 8^{th} and 9^{th} minutes using an AMTI (AMTI Force and Motion, Watertown, MA), force plate equipped, dual belt treadmill and a Vicon motion capture system (Vicon, Centennial, CO). The order of the footwear conditions was randomized. After all testing was completed the markers were removed and the participant changed back into their personal clothing.

Data Analysis

Visual 3D software (V3D) (C-motion, Inc., Germantown, MD) was used to process the kinetic and kinematic data. A 4th order, digital Butterworth filter was applied with cutoff frequencies of 6 Hz and 10 Hz for kinematic and kinetic data respectively. A threshold equal to 5% of a participant's body weight was applied to the vertical ground reaction force in order to identify foot contact events. Heel-on and toe-off for 100-foot contacts (50-left, 50-right) collected over 60 seconds were automatically identified by V3D**,** defined as the first and final frames the vertical GRF vector surpassed the 5% force threshold. In addition, automatic gait events, as assigned by V3D, were visually corrected by a single researcher to align with force vector appearance and disappearance. Irregular foot contacts, identified by examining the vertical ground reaction force, were marked for exclusion during exportation from V3D. Center of pressure was calculated using the measured moments, known origin of the force plate, and ground reaction forces. COP data were then processing using a custom Matlab (Mathworks, Natick, MA) software that analyzed the variability of COP displacement in the medial-lateral (ML) and anterior-posterior (AP) direction as well as a total displacement value following the methodology as describe by Bizovska et al. (2014) (Table 1).

Table 3.1

Description of observed variables.

Displacement	Description	Computation
ML	Medial-Lateral Displacement	$D_{ML} = \lvert X_i - X_{i-1} \rvert$
AP	Anterior-Posterior Displacement	$D_{ML} = \lvert Y_i - Y_{i-1} \rvert$
Total	Total Displacement	$D_{Total} = \sqrt{D_{ML}^2 + D_{AP}^2}$

*Equations sourced from Bizovska et al. (2014)

Statistical Analysis

For each quadrant, the mean values of the standard deviations in the ML and AP directions as well as the mean of the standard deviation of the total displacement were used for further analyses. A single MANOVA was used to determine effects of footwear (within-subject independent variable) and limb (between-subject independent variable) for each quadrant with the probability of a Type I error set at 0.05. A total of 12 dependent variables were used in the MANOVA (4 quadrants, 3 directional measures). Statistical analysis was performed using SPSS software (IBM, Armonk, NY, USA).

Results

From each MANOVA, a statistically significant main effect was identified for footwear, but no interactions were found. Identical results were found for AP measures and for total displacement, therefore, only AP data are shown in Table 2. A significant main effect for feet was identified in only the ML direction for Q1 and Q4; left feet displayed greater variability than right feet.

Regarding differences in footwear conditions in the AP direction, the shod condition produced greater variability in Q1, whereas the unshod condition produced significantly greater variability in Q2 through Q4. Between footwear conditions in the

ML direction, the shod condition produced significantly more variability in Q1 whereas the unshod condition produced significantly more variability in Q4.

Table 3.2
Standard deviations for all quadrants, all conditions.

	Q1**				**Q2**				**Q3**				**Q4****			
	Shod		**Unshod**		**Shod**		**Unshod**		**Shod**		**Unshod**		**Shod**		**Unshod**	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
R, ML	0.55*	0.16	0.49	0.17	0.29	0.08	0.32	0.16	0.34	0.14	0.40	0.14	1.82	0.82	2.60*	1.40
R, AP	1.86*	0.54	1.31	0.50	0.99	0.31	1.20*	0.30	1.03	0.22	1.13*	0.38*	0.66	0.31	0.92*	0.51
L, ML	0.80*	0.40	0.53	0.26	0.32	0.15	0.26	0.12	0.36	0.18	0.34	0.15	2.91	1.60	3.2*	1.40
L, AP	1.74*	0.54	1.26	0.47	1.01	0.25	1.26*	0.31	1.06	0.27	1.21*	0.44*	0.68	0.3	1.14*	0.68

R=right, L=left. *shows significantly greater footwear condition; **ML, L > R.

Discussion

The results of the current study show higher variability in unshod compared to shod conditions. Bizovska et al. (2014), the work that motivated the present study, showed that higher COP gait variability is demonstrated in older adults when compared to younger people. The findings of the present study, combined with those of Bizovska et al., underscore the recommendation put forth by previously mentioned researchers that the elderly should wear shoes when walking, regardless of location. This is especially important in the home where falls are most prevalent (Menz et al., 2006).

The most important finding of this study was that the unshod footwear condition resulted in greater COP variability in three of the four quadrants (Q2-Q4) except for the ML direction in Q2 and Q3. The greater variability found in the AP direction in the unshod condition over Q2-Q4 may be explained, in part, by the consequences of the rigid structure of modern footwear on gait. These include inhibiting foot motion (i.e., eversion, adduction, external rotation, and forefoot torsion), providing a larger base of support with which force is dispersed (i.e., obscuring fine COP directional changes when measured) , and reducing step-to-step arch length variation (i.e. greater consistency of foot loading step to step) (Morio, Lake, Gueguen, Rao, & Baly, 2009; Nyska, Mccabe, Linge, Laing, & Klenerman, 1995; Wolf et al., 2008). Each of these factors may act to increase the consistency with how the foot experiences load during stance and is measured, reducing the COP trajectory variability when shod.

In addition to the higher variability for the shod condition found in Q2-Q4 another result of note is the variability in Q1. Unshod COP variability in Q1 was lower, compared to the shod condition, in both the AP and ML directions. This difference may be explained by the results of previous research comparing shod and unshod walking. Kinematic and kinetic characteristics when walking without footwear include greater plantarflexion at heel-strike (i.e., a flatter foot position at contact), an earlier vertical ground reaction force impact peak, and a higher loading rate. (Bishop, Fiolkowski, Conrad, Brunt, & Horodyski, 2006; Morio et al., 2009; Wit, Clercq, & Aerts, 2000). Within the context of the present study, these gait tendencies when unshod translate into a shorter duration for Q1. Therefore, fewer data points are considered when calculating the COP which diminishes the likelihood of seeing high step-to-step variability. This finding is of particular note as Bizovska et al. (2014) concluded the higher variability found in Q1 and Q4 of their study, as compared to Q2 and Q3, signified these quadrants to be the least stable during stance, a conclusion supported by previous literature (Chiu, Wu, & Chang, 2013). This finding is in conflict with the premise that footwear provides a more stable base on which to walk and is worth further investigation.

These data, more specifically the unshod data, demonstrate some interesting differences when compared to the results of Bizovska et al. (2014) in their "younger" group. In Q1 the current study found lower levels of COP variability in the AP and ML direction (60% to 70%) as compared to Bizovska et al. (2014) younger group however, in Q2 and Q3 greater levels of variability were observed in both directions (35% to 40%). Across all quadrants, Bizovska et al. (2014) found AP variability to be greater than ML whereas the current study found Q4 ML variability to be greater than AP. In Q4 the current study found greater ML variability as compared to AP variability while Bizovska et al. (2014) found the opposite. Direct comparisons to younger and elder groups of Bizovska et al. (2014) show large differences. While these results differ, possibly due to differences in collection method and number of steps analyzed, the differences further underscore the need to divide stance into phases to better understand the dynamics of walking gait.

The results comparing limb COP show an asymmetry of greater ML displacement variability in quadrants one and four of the left limb. While its presence is consistent with previous literature investigating both walking and running that found existing levels of interlimb asymmetry in healthy populations, finding greater variability under the left limb is unexpected. (Belli, Lacour, Komi, Candau, & Denis, 1995; Furlong & Egginton, 2018; Lathrop-lambach et al., 2014; Maupas, Paysant, Martinet, & Andr, 1999). Of the 20 individuals who participated in this study, 18 reported right-foot dominance as determined by answering the question, “which limb would you use to kick a soccer ball as far as possible with the highest degree of accuracy?”. Literature on foot dominance would suggest the non-dominant foot, in 18 of 20 participants this being the left, should be expected to show less COP variability as it provides postural and stabilizing support (Peters, 1988). The exact reason for this result is unclear.

Limitations

In the present study, all data were collected on an instrumented treadmill with two force plates below separate, front-and-back belts. The effects of the treadmill are two fold, the treadmill may have artificially reduced the variability of COP and the treadmill resulted in methodological constraints impacting the vGRF profile potentially altering quadrant lengths (De la Cruz et al., 2016). Additionally, while comparisons to Bizovksa et al. (2014) are insightful, and certain elements such as sampling rates were identical between the two studies, a true comparison cannot be made to other methodological differences. These include such things as the number of steps analyzed, 50 vs 5, and differences in customized software.

Conclusions

This study found footwear to impact the variability of step-to-step COP trajectories in a young healthy female population. The hypothesis of this study was partially confirmed as the footwear condition produced decreased AP COP variability in Q2-Q4. It was also partially rejected as the shod condition also produced greater variability in both AP and ML directions in Q1. Extrapolating these results to older adults, it is suggested that unshod footwear conditions should be minimized in this population so that COP variability during gait is minimized. A future direction of this research will certainly examine the difference in COP gait variability between unshod and shod footwear conditions in older populations.

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CHAPTER IV

RESULTS and DISCUSSION

Results

From each MANOVA, a statistically significant main effect was identified for footwear, but no interactions were found. Identical results were found for AP measures and for total displacement, therefore, only AP data are shown in Table 2. A significant main effect for feet was identified in only the ML direction for Q1 and Q4; left feet displayed greater variability than right feet.

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Table 4.1
Standard deviations for all quadrants, all conditions.

	Q1**				**Q2**				**Q3**				**Q4****			
	Shod		**Unshod**		**Shod**		**Unshod**		**Shod**		**Unshod**		**Shod**		**Unshod**	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
R, ML	0.55*	0.16	0.49	0.17	0.29	0.08	0.32	0.16	0.34	0.14	0.40	0.14	1.82	0.82	2.60*	1.40
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In the present study, all data were collected on an instrumented treadmill with two force plates below separate, front-and-back belts. The effects of the treadmill are two fold, the treadmill may have artificially reduced the variability of COP and the treadmill resulted in methodological constraints impacting the vGRF profile potentially altering quadrant lengths (De la Cruz et al., 2016). Additionally, while comparisons to Bizovksa et al. (2014) are insightful, and certain elements such as sampling rates were identical between the two studies, a true comparison cannot be made to other methodological differences. These include such things as the number of steps analyzed, 50 vs 5, and differences in customized software.

Conclusions

This study found footwear to impact the variability of step-to-step COP trajectories in a young healthy female population. The hypothesis of this study was partially confirmed as the footwear condition produced decreased AP COP variability in Q2-Q4. It was also partially rejected as the shod condition also produced greater variability in both AP and ML directions in Q1. Extrapolating these results to older adults, it is suggested that unshod footwear conditions should be minimized in this population so that COP variability during gait is minimized. A future direction of this research will certainly examine the difference in COP gait variability between unshod and shod footwear conditions in older populations.

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Appendix

Institutional Review Board Approval

UNIVERSITY OF
NORTHERN COLORADO

Institutional Review Board

DATE:	June 26, 2018
TO:	Gary Heise
FROM:	University of Northern Colorado (UNCO) IRB
PROJECT TITLE:	[1258862-2] Biomechanical comparison between shod and unshod walking
SUBMISSION TYPE:	Amendment/Modification
ACTION:	APPROVED
APPROVAL DATE:	June 26, 2018
EXPIRATION DATE:	June 25, 2019
REVIEW TYPE:	Expedited Review

Thank you for your submission of Amendment/Modification materials for this project. The University of Northern Colorado (UNCO) IRB has APPROVED your submission. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on applicable federal regulations.

Please remember that informed consent is a process beginning with a description of the project and insurance of participant understanding. Informed consent must continue throughout the project via a dialogue between the researcher and research participant. Federal regulations require that each participant receives a copy of the consent document.

Please note that any revision to previously approved materials must be approved by this committee prior to initiation. Please use the appropriate revision forms for this procedure.

All UNANTICIPATED PROBLEMS involving risks to subjects or others and SERIOUS and UNEXPECTED adverse events must be reported promptly to this office.

All NON-COMPLIANCE issues or COMPLAINTS regarding this project must be reported promptly to this office.

Based on the risks, this project requires continuing review by this committee on an annual basis. Please use the appropriate forms for this procedure. Your documentation for continuing review must be received with sufficient time for review and continued approval before the expiration date of June 25, 2019.

Please note that all research records must be retained for a minimum of three years after the completion of the project.

If you have any questions, please contact Sherry May at 970-351-1910 or Sherry.May@unco.edu. Please include your project title and reference number in all correspondence with this committee.

Dr. Heise and research team -

Thank you for your patience with the IRB process. The amended and revised materials have been approved by the first reviewer, Wendy Highby. Subsequently, I reviewed the original and revised materials and have also recommended approval. Be sure to use the amended/revised and additional materials in your participant recruitment and collection of data.

Best wishes with your research.

Sincerely,

Dr. Megan Stellino, UNC IRB Co-Chair

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within University of Northern Colorado (UNCO) IRB's records.