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A THESIS

Submitted to the Department of Kinesiology and Health in the College of Education and Human Development, Georgia State University

In partial fulfillment of the requirements for the degree of Master of Science in Exercise Science

By

Jiyun Ahn

Fall 2020

Approved by:

Feng Yang, Ph.D., Committee Chair

Jianhua Jerry Wu, Ph.D., Committee Member

Pey-Shan Wen, OTR/L, Ph.D., Committee Member

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Abstract

Previous studies have tackled the effect of sole thickness on falls and suggested a significant relationship between the sole thickness and fall risk. However, the prior studies were based on qualitative survey. No quantitative studies have been conducted to closely examine the causal effect of the sole thickness on the risk of falls. The purpose of this cross-sectional study was to explore the effect of the sole thickness on fall risk and the body's reactions in response to an unexpected slip during stance among young adults. Our overall hypothesis was that thick soles would impair dynamic stability, delay the body's reactions to the external slip perturbation, and show effective reactional muscle activation. Specifically, I hypothesized that 1) individuals in the groups with thin soles would display greater dynamic stability than the thick groups at recovery step onset and touchdown; 2) the step latency in the thin sole groups would be shorter than the thick groups, contributing to the observed higher stability; and 3) the leg muscles would be activated faster along with a lesser EMG burst in the thin-soled groups than thick-soled groups. Nine young adults aged between 18 and 45 years were recruited and evenly randomized into three groups in terms of the thickness of the sole: barefoot (0 mm), thin (5 mm), and thick (10 mm). After warmup exercise and the familiarization process with the assigned sole, all groups experienced an identical unexpected stance-slip perturbation induced by quickly moving the treadmill belt. Full-body kinematics were collected by a motion capture system and used to calculate the kinematics of the body's center of mass (COM). Then dynamic gait stability, as the primary outcome measure, was determined based on the COM's position and velocity relative to the base of support. Other spatiotemporal parameters and electromyography of leg muscles after the slip were the secondary outcome measures, including the recovery step latency, duration, length, slip distance, muscle latency, and the EMG burst. Both the primary and secondary outcomes were compared among groups by using one-way ANOVA followed by appropriate post-hoc tests to test three hypotheses. The results showed instable balance status at the initiation of the recovery step with the thicker soles, changes in spatiotemporal parameters such as a prolonged step latency and duration and larger step length, and a shorter EMG latency and lower EMG burst in TA and GA. This study will advance our understanding of the influence of sole thickness on the risk of falls.

Key words: fall prevention, shoes sole thickness, dynamic gait stability, slipping

Contents

Introduction

Falls are a critical issue which can lead to injury and even death among various populations, especially in the elderly (Kannus et al., 2005). About one third of community living people aged over 75 experience a fall at least once a year (Tinetti et al., 1988). According to a previous study, a high proportion of the elderly people wears inappropriate shoes, which has been identified as a key risk factor of falls in older adult (Menant et al., 2008). Among mechanical properties of the shoes such as collar height, tread and heel geometry, and firmness of the sole, the sole thickness has been highlighted as a major contributor to falls in older adults (Menant et al., 2008). Thus, it is important that guidelines regarding the selection of appropriate footwear, particularly in terms of the thickness of the soles, are established. A precondition for developing such guidelines is to systematically investigate how the sole thickness alters the risk of falls.

A couple of studies have tackled the effect of sole thickness on falls and suggested a significant relationship between the sole thickness and fall risk. For example, a systematic review concluded that thick-soled shoes could negatively affect postural stability, thus increase the risk of falls (Menant et al., 2008). Another survey-based research found that the shoes with thick soles changes the spatiotemporal gait parameters such as the step length and raise the likelihood of falls in older adults (Tencer et al., 2004).

Although the findings are meaningful, the approaches used in the previous studies had limitations. First, the collection of falls data is primarily based on recounting incidences based on memory. This method is subject to inaccuracy, bias, and omission resulting from deteriorated memory or cognitive dysfunction in seniors (Moreland et al., 2004), and decreasing the reliability of data on fall incidence (Jenkins et al., 2002). Second, the physical activity level and the exposure to possible fall hazards affect the likelihood of falling in older adults. The self-report method does not account for these factors, possibly leading to underestimation of actual fall counts (Graafmans et al., 2003). There could be a trade-off between the exposure to fall hazards and the risk of falls among older adults (Horlings et al., 2008). For instance, those who are physically inactive might be more prone to falls due to physical limitations, but may also have the least exposure to conditions that might induce falls; while the most active ones, who might be less prone to falls, have high exposure to fall hazards leading to high likelihood of falling. Third, the self-reported data often lack information on the specific details such as the types and circumstances of falls of the actual falls (Feldman and Robinovitch, 2006), which likely vary considerably from person to person. Without considering or controlling for the circumstances of falls and the level of the exposure to fall hazards, it is very difficult, if not impossible, to precisely investigate the relationship between shoe sole thickness and the risk of falls. Forth, no study has specifically inspected in a quantitative way the effects of the sole thickness on body balance and fall risk. Therefore, the findings from previous studies regarding the effects of sole thickness are always confounded by other factors, such as collar height, sole firmness, and the tread of the sole.

Last, the retrospective falls collection using self-reported methods were usually a significant period (weeks or months) away from the evaluation of the footwear (Connell and Wolf, 1997; Tencer et al., 2004). This mismatch raises another major concern as to how accurately the findings derived from the information collected at various time instants reflect the real causal-effect linkage between fall incidences and the sole thickness. The only way to accurately quantify the relationship between sole thickness and falls is to evaluate how all subjects respond to the same gait perturbation administered in a controlled laboratory condition and to evaluate the sole thickness at the same time as the laboratory-induced gait perturbations.

Overall, the literature, primarily based on survey data, indicates that the thickness of the sole impacts the risk of falls. Specifically, the thicker the sole, the greater the risk of falls (Menant et al., 2008; Robbins et al., 1992; Robbins et al., 1994; Tencer et al., 2004). However, the mechanisms behind this notion are unclear. A candidate one is that the thin soles, in comparison to their thick counterparts, would have less delay for the central nervous system to sense the sudden and unexpected disturbance to the body's normal posture and thus to take appropriate reactions to correct the posture if necessary. In this connection, the risk of falls following a perturbation could be reduced if the sole is thin (Robbins et al., 1992). On the other hand, the shoes with thick sole would slow down the detection of an external perturbation and thus delay the reactions to the balance disturbance after the perturbation (Menant et al., 2008; Robbins et al., 1992; Robbins et al., 1994; Tencer et al., 2004). Although this mechanism seems intuitive, no study has verified it. The lack of a full understanding of the influence of sole thickness on body balance and fall risk will likely affect the development of the guidelines for selecting footwear for people with high risk of falls.

Given that several limitations were found in the previous studies, there is a need for a novel study with a highly controlled environment and a verified assessment way to precisely examine the effect of the sole thickness on the fall risk. As an initial effort along this line of research, it is logical to select a common but fundamental human posture to examine how the sole thickness changes the risk of falls after an external perturbation, in particular a slip. In this thesis work, the slip perturbation induced during human standing was chosen. According to a previous study, the ActiveStep treadmill (Simbex, NH) is a useful platform to induce slip perturbation during standing and thus assess the body's subsequent reactions. In that study, the authors used an ActiveStep treadmill to successfully create the slip perturbation with desired slip distance, velocity, and acceleration level during standing (Yang et al., 2018b). Therefore, this project used the same treadmill to expose the participants to unexpected stance-slip perturbations and monitor their body's response while wearing soles with different thicknesses. The slip was chosen as the perturbation because slip-related falls account for up to 40% of all outdoor falls in older adults (Luukinen et al., 2000).

Human body is inherently unstable given its multi-segment structure, high center of mass (COM), but small base of support (BOS). Traditionally, body balance is defined solely based on the relative position of the COM to the BOS. For a person who is standing, whenever the projection of the COM is within the BOS, the person can maintain the balance. However, this concept is not applicable to a dynamic situation when the COM gains significant velocity, such as when a person's reaction to an external perturbation. The theory of Feasible Stability Region (FSR) has been recently developed to study balance during a dynamic task (Fig. 1) (Pai and Patton, 1997; Pai et al., 2006). According to the FSR, in addition to considering the relative position of the COM to the BOS, the relative velocity of the COM to the BOS should be taken into account. The FSR is enclosed by two boundaries: the boundary against backward falling and the one against forward falling. When the COM's motion state (the combination of the COM position and velocity relative to the BOS) is within the FSR, the person can maintain the balanced posture without the need to change the BOS. When the COM motion state is below the boundary against backward falling, the COM lacks sufficient forward momentum to bring the COM above the BOS when the COM's velocity diminishes. A person will experience a backward balance loss. To prevent a backward fall, the person must take an effective recovery step. If the recovery step is unsuccessful, the person will fall backwards, as induced by a slip perturbation. Conversely, a COM motion state above the boundary against forward falling possesses excessive forward momentum which would carry the COM forward and beyond the BOS, leading to a forward balance loss. The person must execute a forward recovery step to prevent the body from falling forward. An unsuccessful recovery step will lead to a fall forward. The FSR theory was derived using computer simulation and verified by massive experimental data (Yang, 2016). Dynamic stability based on the FSR provides us a novel perspective to investigate the body’s risk of falls and thus the recovery from a balance loss resulting from an external perturbation. An examination of the influence of the sole thickness on dynamic stability will help us understand how the sole thickness affects the risk of falls after a perturbation.

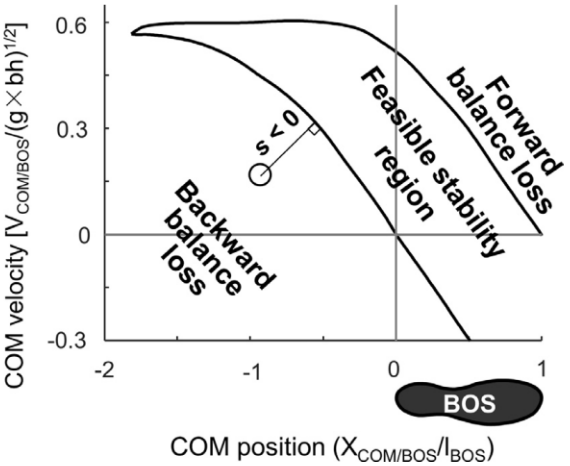


Figure 1. Schematic illustration of Feasible Stability Region (FSR). The upper and lower boundaries indicate the threshold against forward and backward balance loss respectively. *s* (the length of the thin line) represents the dynamic stability, which is considered the shortest distance between the COM motion state and the backward balance loss boundary. COM motion state inside the FSR, which has positive value, reflects stable body’s balance status. When the motion state is below the lower boundary, it has a negative value. In this case the body’s momentum is not enough to move the body forward, thus would cause backward falling. In contrast, when the motion state is beyond upper boundary, the body has excessive forward momentum and would experience forward balance loss.

Besides dynamic stability, some other spatiotemporal parameters could be used to quantify the body's responses to an external perturbation. For example, the step latency, that measures how quickly the recovery step is initiated after a perturbation, the step duration, that indicates how quickly the recovery step is being executed, the step length, that quantifies how effective a recovery step restores body balance and normalized by the body height, and slip distance, the slipped length on the first recovery side and normalized by the body height, can be adopted to further examine how the sole thickness impacts the recovery process following a perturbation.

Electromyography (EMG) is a widely used parameter measuring the neuromuscular activities in the literature. EMG analysis could help analyze the muscle activity patterns during slip-related perturbation to identify the body's reactive movements on musculoskeletal level (Chambers and Cham, 2007; Sakai et al., 2008; Tang et al., 1998). In detail, the latency of leg muscles, which is the time taken to activate a muscle to respond to a perturbation, and EMG burst, which reveals the maximum burst of muscle activation after a slip normalized by the EMG burst during overground normal walking, can be used to support our theory that the thicker soles delays the reactional movements after a slip-related perturbation.

The principal purpose of this thesis project was to explore how the sole thickness affects the risk of falls after an unexpected external perturbation, particularly a slip during stance. The fall risk was measured by dynamic gait stability after the slip perturbation. As the first study of its kind, we started with young adults. Specifically, we monitored and compared the body's reactions to the unexpected stance-slip perturbation between three different sole thickness (barefoot group vs. 5 mm group vs. 10 mm group) to determine the possible effects of sole thickness on the risk of falls and relevant parameters following an unexpected slip induced during stance among young adults. Dynamic stability was our primary outcome measure and other spatiotemporal parameters (step latency, step duration, step length, and slip distance) and EMG data (EMG latency and EMG burst) were the secondary and explanatory outcome measures.

Statement of Question

The primary purpose of this study was to examine how the sole thickness affects the risk of falls after an unexpected slip perturbation during standing among young adults. Three sets of sole with different thicknesses were tested. This project could potentially extend our understanding of sole thickness as a contributing factor among shoe properties to falls. The results from this study could inform the development of the guidelines for choosing the footwear for individuals with elevated risk of falls.

Rationale

No study has been carried out to quantify the causal relationship between the sole thickness and the risk of falls. The exact influence of sole thickness on the fall risk remains unclear, possibly hindering the effort of preventing falls among individuals with high risk of falls from the perspective of wearing appropriate shoes. Therefore, it is imperative to identify how the variation of the sole thickness alters the risk of falls and the postural stability. A sound understanding of the impact of the sole thickness on fall risk will undoubtedly furnish references to optimize the footwear characteristics from the viewpoint of preventing falls.

Hypotheses

It was hypothesized that:

(1) The increased shoe sole thickness will impair dynamic stability following an unexpected slip perturbation. Specifically, groups with thick soles (10- or 5-mm) will be more instable than the groups with thin soles (5- or 0-mm) following the unanticipated standing-slip.

(2) The thicker shoe soles will delay the body's reactions to the slip perturbation and reduce the effectiveness of the reactions. In detail, we anticipate a prolonged recovery step latency, a reduced recovery step duration, a shorter recovery step length, and a longer slip distance after a slip among groups with thicker soles than groups with thinner soles.

(3) The thicker sole groups will show less effective muscle activation in response to a slip than the thin sole groups. Particularly, there will be a longer EMG latency and a greater EMG burst with thicker soles than the thinner soles.

Delimitations and Limitations

This study had several limitations. First, healthy young adults were recruited. The findings from this study may not be generalizable to other populations such as the older adults or people with neurological diseases who have higher risk of falls. However, as the first attempt in this line of research, the current study will provide useful information for conducting similar studies in populations with high risk of falls. Second, only two sole thicknesses (5 mm and 10 mm) in addition to the barefoot condition (0 mm) were examined. This limited thickness range may not provide direct information about the influence of sole thicker than 10- mm on body's recovery effort from an external perturbation. Third, only soles with constant thickness were applied to the subject's barefoot to remove the potential mechanical effects from the other shoe characteristics such as shoe collar height, tightness, and firmness. Forth, only slip perturbations during standing were used to perturb a participant. It is unknown whether the findings from this study can be generalized to other types of perturbation such as trip or during different type of locomotion such as gait. Fifth, this study was conducted in a laboratory environment. Although being well controlled, it differs from the natural everyday living condition. Thus, the generalizability of the findings from this study to real-life situation is unclear. Sixth, the firmness of the sole was not measured, therefore, the effects of the firmness of the sole is unknown. However, the level of firmness of the sole was constant among all participants, thus the impacts of the firmness of the sole was controlled. Seventh, the interaction between plantar and contact surfaces was not controlled across the groups. The subjects in barefoot group touched the floor with their barefoot directly, while the subjects with soles contacted their barefoot to the sole. This discrepancy cannot explain the effects of variations of friction force and tactile stimuli on the plantar sensation among groups when the subjects reacted to the slip. Lastly, only nine participants were recruited. This small sample size could lead to a large variation and thus confound the results. Further large-scale studies are needed to address these limitations.

Definitions

In this study, the following terms will be used:

- Perturbation: a disturbance or disruption exerted unexpectedly to normal human locomotion or posture.

- Recovery step: the first backward step following the onset of the slip taken a participant to restore the body’s balance.
- Step latency: the time interval from the treadmill belt slip onset to the instant of liftoff of the recovery step.
- Step duration: the period of time elapsed from the liftoff of the recovery step to its touchdown.
- Step length: the anteroposterior distance between heels at the recovery foot touchdown normalized by the body height.
- Slip distance: the distance of the slip on the first recovery side normalized by the body height.
- Center of mass (COM): the average position of all body segments, weighted according to their masses.
- Base of support (BOS): the contact area between the feet and the ground.
- Feasible Stability Region (FSR): the collection of all possible COM’s motion state which can maintain a balanced upright body posture without changing the BOS on the COM velocity-position phase space. This region is enclosed by two limits: the limit against backward falling and the limit against forward falling. The former will be used in this thesis project as the slip perturbation is the focus of this project.
- Dynamic stability: a measurement of body’s level of fall risk by considering the kinematic relationship between the body’s COM and BOS.
- EMG latency: the time interval from the slip onset to the onset of the muscle activation.

- EMG burst: the maximum value of EMG burst during slip-related perturbation normalized to the peak EMG signal during normal walking.

Review of Literature

Introduction

It is a consensus that falls are a serious accident resulting in severe injuries such as fracture, disability, and even death among older adults (Lord et al., 2001) and people with movement dysfunction (Li et al., 2006). About 30% of the people aged over 65 experience falls, and more than 50% of falls occurs outdoors (Lord et al., 1994). It is therefore essential to strengthen the defense against falls among individuals with high risk of falls. The first and the most important step is to identify the risk factors associated with falls.

Although studies inspecting the influence of sole thickness on the risk of falls are scarce, the limited studies unanimously suggest that footwear is related to the risk of falls (Menant et al., 2008; Robbins et al., 1994; Tencer et al., 2004). For example, the sole thickness is thought to be a main mechanical property of the shoes which could be manipulated to prevent fall accidents (Menant et al., 2008). Several studies have specifically focused on examining hazardous impact of soles on hindering the balance maintenance among adults. Steven Robbins et al. (1992) found a negative relationship between the shoe sole thickness and body stability through a balance beam test. This study concluded that the impaired body stability is associated with the high sole thickness among older adults (Robbins et al., 1992). In another study by the same authors (Robbins et al., 1994), the test based on the balance beam confirmed the conclusion that the thicker sole is related to a higher fall rate than thinner sole among older adults. In addition, Tencer et al. (2004) conducted a survey-based research to study how the biomechanical properties of shoes affect the risk of falls in older people. The authors concluded that older adults who wear thick-soled shoes showed nearly twice higher fall incidence than the people with thin-soled shoes (Tencer et al., 2004).

While the current literature congrously suggests that the thicker soles could negatively impact the balance maintenance and increase the risk of falls, no study has directly and quantatively characterized the effect of sole thickness on the risk of falls using a rigorous study design to eliminate the possible confoundings from other factors. For instance, Steven Robbins, Gouw, & McClaran (1992) used customed shoes with different thicknesses and firmnesses in both two studies, which introduced possible confounders from the shoe design. In addition, walking performance on the balance beam, which was used in preivous studies (Robbins et al., 1992), may not appropriately represent the effect of soles on human gait over ground. Frequency of balance failures from repeated walking trials used as the only outcome measure in these studies could also limit the application of the findings with the lack of consideration for the training effect. Furthermore, in the surveilance study from Tencer et al. (2004), direct impact from the sole thickness is unclear due to the variation of the types of the shoes reported. Therefore, there is a need to testify the exclulsive role of the sole thickeness in contributing to the risk of falls.

Mechanism

It is believed that body balance is controlled by three sub-systems: the visual system, the vestibular system, and the proprioception system (Woollacott and Shumway-Cook, 1990). An impediment of any of the three systems could challenge the maintenance of balance. After an unexpected external perturbation, the sensory information from these three systems are required to execute a quick and effective recovery process to restore the body’s balance. With the vision and vestibular systems intact, any deviation to the proprioception system could affect the body’s recovery effort. The possible explanation of the detrimental effect of thick soles on balance equilibrium is that a thicker sole may obstruct the proprioception system. Specifically, with the thick soles, one could experience the sensation with poor foot position awareness following an external perturbation (Menant et al., 2008; Tencer et al., 2004). Sensation from plantar side plays an important role in stability control in human (Robbins et al., 1994). The sensory insulation from the thick soles impedes the delivery or reduce the level of the sensory information from plantar mechanoreceptor to the central nervous system. As a result, the reactional movements could be delayed after perturbation, thus increasing the likelihood of a fall (Kavounoudias et al., 1998; Robbins et al., 1994). On the other hand, thin-soled shoes provide a better and sensitive detection of external mechanical stimulus and help maintain stability. In this thesis project, the sole thickness was the only factor of our interest with all other factors well controlled. Therefore, we anticipated the results from the present study could verify the previous postulation that thick soles increase the risk of falls.

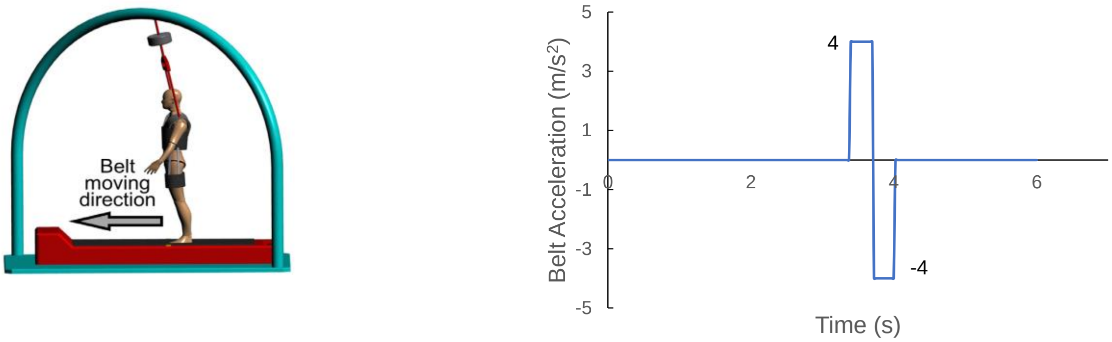
Slip Perturbation

Slipping is a major environmental hazard which causes outdoor falls among the elderly (Li et al., 2006), and triggers about 40% of falls occurred on the same level (Courtney et al., 2001). Given that the high proportion of falls comes from slip events, it is crucial to reduce the probability of slip-related falls in order to prevent fall related outcomes such as injuries and death (Kannus et al., 2005; Tinetti and Williams, 1997).

As mentioned, we chose the standing-slip as the perturbation in this first-of-kind study (Fig. 2). The primary reason of adopting standing-slip was to further eliminate the potential confounding effects from other uncontrolled factors. For example, during gait, different persons could take different step lengths, walk at different gait speeds, and land the foot at different angles. If a slip was induced during gait, the potential effects from the diversity of those uncontrolled variables could confound the results supposedly focus on the effects of sole thickness on fall risk after a slip. By contrast, a slip induced during standing would remove the biases resulting from those parameters, allowing us to pinpoint the contribution of sole thickness to the change in fall risk after a slip perturbation. Without any doubt, the findings from this study will provide us new knowledge and skills to perturb gait in future.

a) Treadmill for perturbation

b) Belt Acceleration (m/s^2)



c) Belt Velocity (m/s)

d) Belt Displacement (m)

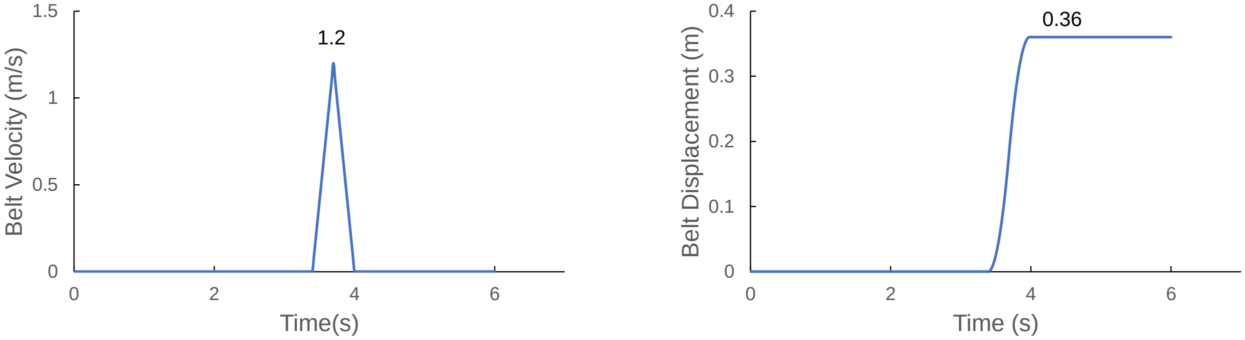


Figure 2. (a) The treadmill used to induce the stance-slip perturbation, and the profile of the slip perturbation induced by the treadmill with (b) an acceleration of 4 m/s^2, (c) a velocity of 1.2 m/s, and (d) a displacement of 0.36 m.

Methods

Participants

This cross-sectional study recruited nine qualified healthy young adults aged between 18 and 45 years (Table 1). To be enrolled, participants had no known acute or chronic neurological or musculoskeletal disease, and experience of a lower extremity injury in the previous three months. The purpose, procedures, and risks of participating in this study were fully explained to each participant prior to obtaining their written informed consent. All participants were randomly and evenly assigned into three groups in terms of the sole thickness: group A (barefoot or thickness = 0 mm), group B (thin or thickness = 5 mm), and group C (thick or thickness = 10 mm). The barefoot group underwent the protocol without footwear. Each group was exposed to a sudden and unexpected stance-slip on a special treadmill. Their body's reactions to the slip were monitored and compared between groups to test our hypotheses. This study has been approved by the Institutional Review Board of Georgia State University (Protocol #: H20192).

Table 1. Comparison of demographic information among three groups.

Group	A (0 mm)	B (5 mm)	C (10 mm)	*p*-value
Number	3	3	3	
Gender (M/F)*	1/2	0/3	1/2	0.53
Age (years)	25 ± 3.00	27 ± 7.21	24 ± 4.00	0.77
Height (m)	1.66 ± 0.11	1.63 ± 0.07	1.68 ± 0.11	0.85
Mass (kg)	69.63 ± 8.13	78.92 ± 22.97	66.73 ± 19.72	0.70

M: male; F: female.

*: χ^2 test was used.

Participants Preparation

After providing the written informed consent, each participant undertook a few anthropometric measurements, such as the body height, body mass, age, gender, knee width, ankle width, ankle height, and foot length. Then, participants in each group were equipped with their assigned footwear condition. Group A was bare footed during the data collection period. Participants in groups B and C were respectively be attached with customized 5-mm and 10-mm soles directly to their feet. The foam used to make the soles was Elmer's White Foam Board (Elmer's Products Inc) (Fig. 3). To ensure that each group of participants were familiar with the respective condition of the sole, participants walked over the ground for about five minutes which can also be considered the warmup.

Before the experiment, 26 reflective markers were placed on the following body landmarks: the top of the head, ears, C7 vertebra, acromion processes, right scapula, elbows, wrists, sacrum, greater trochanters, lateral thighs, lateral femoral epicondyles, lateral tibias, calcanei, lateral malleolus, and base of the fifth metatarsals to capture the full-body kinematics (Yang et al., 2007). An extra marker was placed on the treadmill belt to register the movement of the belt.

To monitor the leg muscle activity, EMG electrodes were placed on bilateral tibialis anterior (TA) and gastrocnemius (GA). Electrode sites were cleaned with alcohol, and skin was shaved, before application of surface electrodes. The electrodes were secured with surgical tape and a compressive wrap. These two muscles were selected based on the literature. Specifically, TA which was described as the most involved muscles to the reactional movements during human walking under perturbation (Chambers and Cham, 2007; Tang et al., 1998) and GA which is the antagonist muscle of TA were primarily investigated for the EMG analysis.

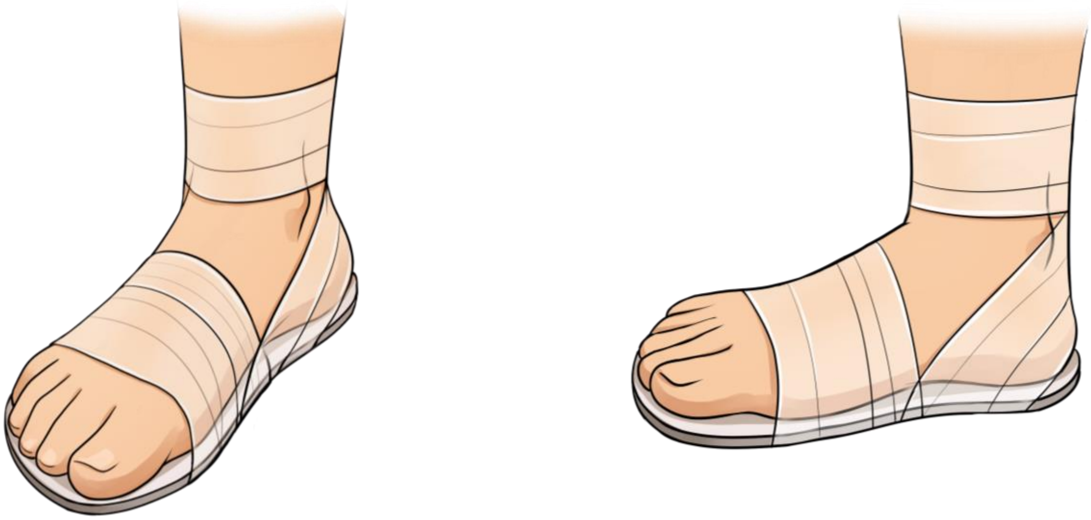


Figure 3. The sole attached to the foot. Foamboards of two constant thicknesses, 5- and 10-mm, were cut into individualized size, attached to the barefoot, and tied with the kinesio-tape.

Experimental Protocol

After the preparation and familiarization, each participant stepped on the ActiveStep treadmill (Simbex, NH) with their corresponding footwear condition and donned the full-body safety harness. The midline of the treadmill was clearly marked on the treadmill surface to guide the proper initial standing position for each trial. After experiencing three standing trials without slip, all groups were notified that “From next trial on, you may or may not experience a slip-like movement. If a slip happens, please try your best to recover your balance and try not to hold onto the ropes.” (Yang et al., 2018a). Two more standing trials were administered, followed by a stance-slip without the participants knowing when and how the slip would happen (Fig. 4). Each trial lasted about 10 seconds. The slip intensity was set with an acceleration of 4 m/s^2, peak velocity of 1.2 m/s, and displacement of 0.36 m (Fig. 2b, 2c, 2d). This concluded the data collection protocol.

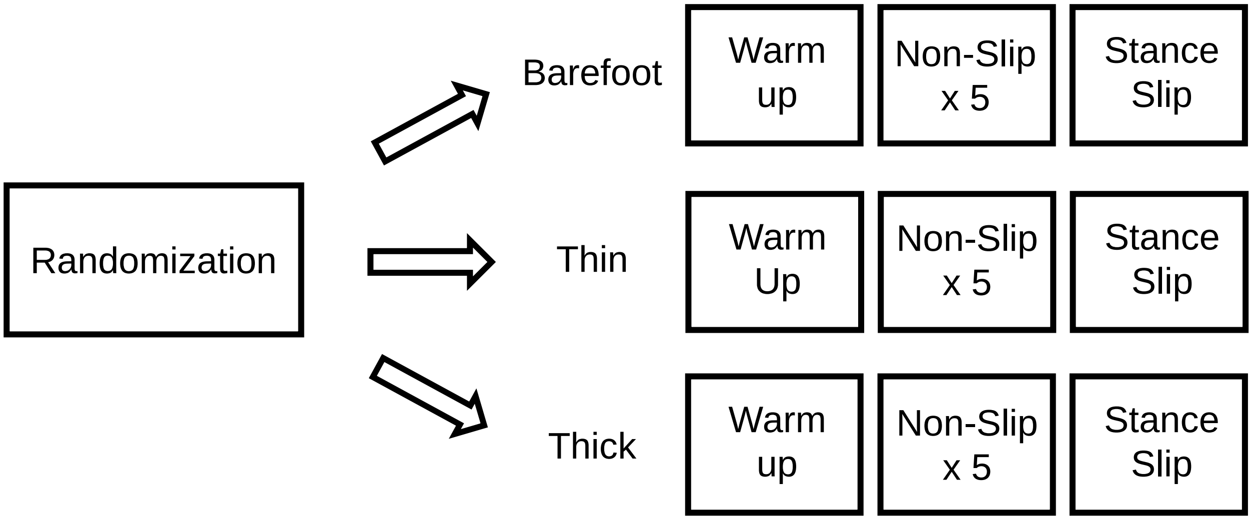


Figure 4. Schematic of the study design used to test out hypotheses. Nine subjects were randomly and evenly assigned into one of three groups; barefoot (0-mm), thin (5-mm), and thick (10-mm) groups. After a warming-up session over ground and five standing trials on the treadmill, all groups experienced an unexpected treadmill-based standing slip.

Full-body kinematics during all treadmill trials were recorded at 100 Hz using an 8-camera motion capture system (Vicon Motion Systems, UK) through 26 reflective markers attached to participants at the body locations with an additional belt-marker. Bilateral lower extremity muscle activity was recorded using a 16-channel Trigno wireless EMG system at 1,000 Hz (Delsys, Natick, MA). The motion capture system and the EMG collection system were synchronized.

Data Analysis

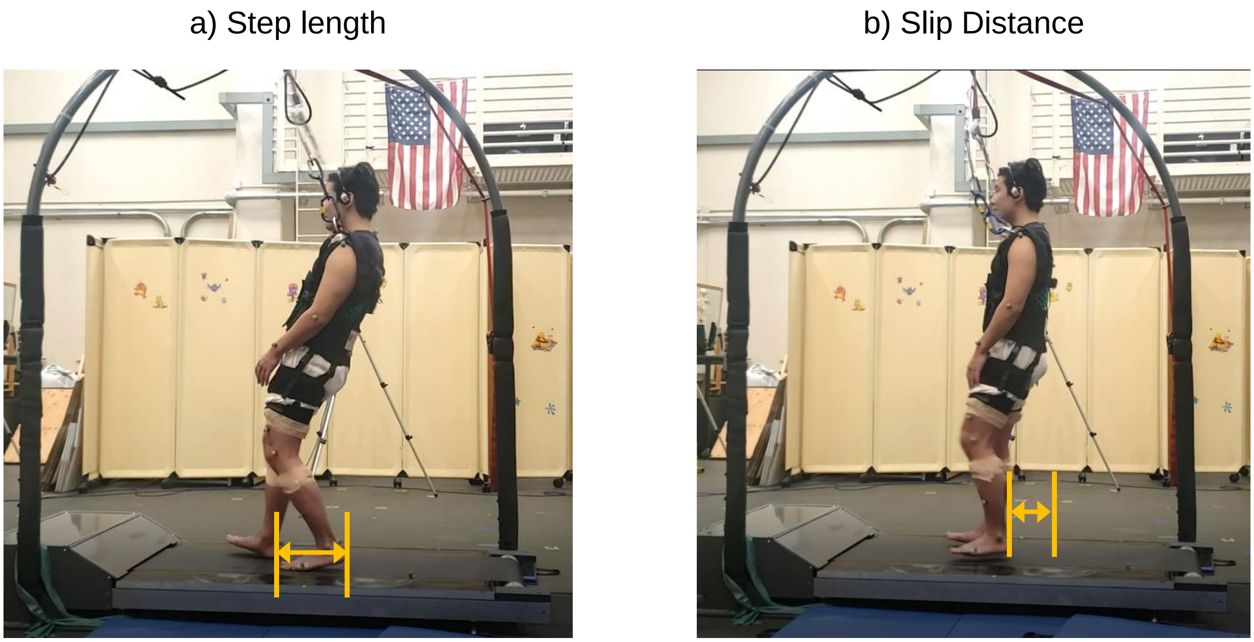
The slip trial was analyzed. Marker paths were low-pass filtered at marker-specific cut-off frequencies (ranging from 4.5 to 9 Hz) using fourth-order, zero-lag Butterworth filters (Yang et al., 2007). Locations of joint centers, heels, and toes were computed from the filtered marker positions. The first backward step after the slip onset was deemed as the first recovery step (or the recovery step) and was analyzed. The timing of three events for the slip trial, belt slip onset

(ON) (Fig. 5a), the liftoff of the recovery foot (LO) (Fig. 5b), and its touchdown (TD) (Fig. 5c) were determined. The belt marker was used to identify the ON. When the belt marker's forward displacement exceeds three standard deviation from its baseline of the first two seconds, the corresponding instant was identified as the ON. The toe and heel markers on the recovery leg were used to determine the LO and TD. The LO is the instant when the height of the toe marker was 5 mm higher than its baseline (Yang et al., 2012). The TD is the moment when the height of either the toe or heel marker dropped within 5 mm from their baseline value after the LO.

Figure 5. Pictures of the events of (a) the belt slip onset (ON), (b) the liftoff (LO) and (c) the touchdown (TD) of the recovery foot.

The body COM kinematics was computed using gender-dependent segmental inertial parameters (de Leva, 1996). The two components of the COM motion state, i.e. its position and velocity were calculated relative to the rear of base of support (BOS) (i.e. the right heel) and normalized by foot length (l_{BOS}) and $\sqrt{g \times bh}$, respectively, where g is the gravitational acceleration and bh the body height. As aforementioned, the stability was calculated as the shortest distance from the COM motion state to the limit against backward balance loss (solid thin line in Fig. 1) (Yang et al., 2016). Dynamic stability was the primary outcome measure.

Temporal measures included the step latency (the duration from ON to LO) and the step duration (the interval from LO to TD). The spatial measures include the recovery step length and the slip distance. The recovery step length was calculated as the anteroposterior distance between heels at the instant of TD and normalized by the body height (Fig. 6a) (Yang et al., 2008) The slip distance was determined as the distance traveled by the first recovery foot between the ON and LO. It was also normalized by the body height (Fig. 6b).



a) Step length

b) Slip Distance

Figure 6. Pictures of (a) the recovery step length and (b) the slip distance of the belt. The yellow dot at the right bottom of (b) represents the original position of the belt marker.

Surface EMG data were digitally bandpass filtered (Butterworth digital, fourth order, zero lag, 20-500 Hz) to attenuate high frequency and low frequency (motion artifact) noise. The data were then rectified and low-pass filtered (Butterworth digital, fourth order, zero lag, 10 Hz cutoff) (Cham and Redfern, 2002). Then, for each muscle, the EMG signal was normalized to the peak value observed during regular walking. The EMG signal during the first two seconds upon the slip was considered its baseline. The EMG onset for each muscle was determined when the respective EMG signal exceeds three standard deviation from its baseline. The EMG latency was calculated as the duration from the treadmill onset to the EMG onset for the corresponding muscle. In addition, EMG burst was determined for each muscle as the maximum value of the EMG amplitude after the EMG onset. The spatiotemporal parameters, the EMG-related measurements were our secondary outcome measures.

Statistical Analysis

To test both hypotheses, one-way analysis of variance (ANOVA) with group being the factor was used to compare both the primary (dynamic stability) and secondary (step latency, duration, and length, and EMG measurements) among groups (Group A vs. B vs. C). If a significant effect of the group was found, independent *t*-tests followed to compare between each pair of groups with Bonferroni corrections. Three hypotheses were tested using a two-tailed α of 0.05 throughout. All statistical analyses were performed using SPSS 24.0 (IBM, NY).

Results

The values of measured variables for each subject are given in the Appendix.

Dynamic Stability

Our results showed that COM position, velocity, and dynamic gait stability at both ON and TD did not exhibit significant difference associated with group ($p > 0.05$ for all, Fig. 7a, 7b, 7c, 7g, 7h, 7i). At LO, there were significant differences among groups in the COM position ($p = 0.02$, Fig. 7d) and stability ($p = 0.04$, Fig. 7f). The COM velocity was not different among groups at LO ($p > 0.05$, Fig. 7e). Follow-up independent *t*-test revealed that the COM position in the thick group was more posterior relative to the BOS than the barefoot group at LO (Fig. 7d, $p = 0.03$). For the dynamic gait stability, the thick group was more instable than the barefoot group at LO ($p = 0.004$, Fig. 7f).

Spatiotemporal Parameters

The spatiotemporal parameters also presented significant group-related differences in the recovery step latency ($p = 0.007$, Fig. 8a) and length ($p = 0.01$. Fig. 8c). Step duration and slip distance were not significantly different among groups ($p = 0.74$, Fig. 8b, 8d). Follow-up independent *t*-tests indicated that the thin and thick groups had a prolonged recovery step latency ($p = 0.02$ for both thin vs. barefoot and thick vs. barefoot, Fig. 8a) and a longer step length ($p = 0.003$ for thick vs. barefoot and $p = 0.03$ for thin vs. barefoot, Fig. 8c) in comparison to the barefoot group. Between the thin and thick groups, only the recovery step latency, but not the recovery step length, displayed significant difference ($p = 0.04$, Fig. 8a).

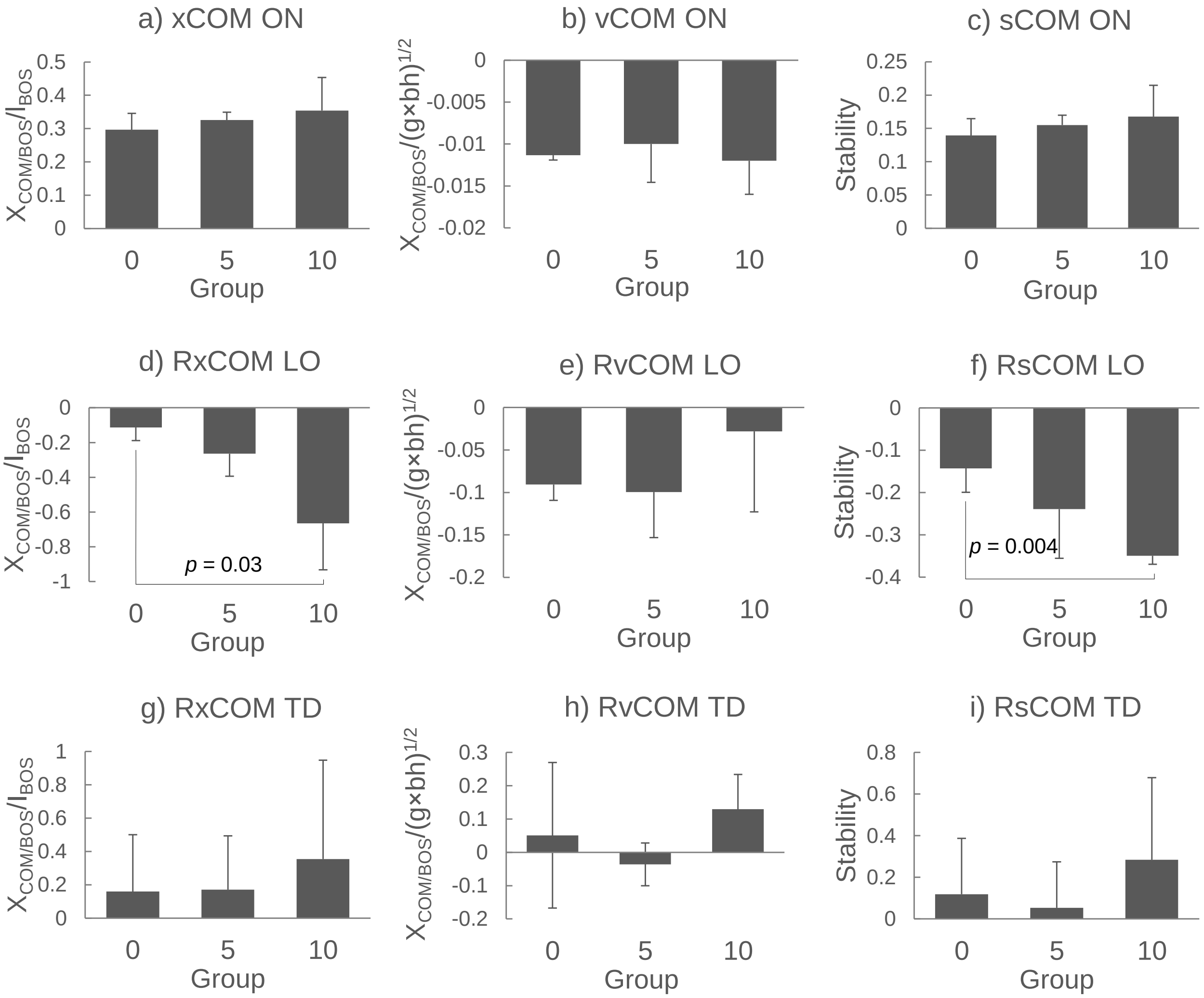


Figure 7. Comparisons of (a) the center of mass (COM) position at the onset of the treadmill belt slip (ON), (b) the COM velocity at ON, (c) the COM stability at ON, (d) the COM position at the recovery step liftoff (LO), (e) the COM velocity at LO, (f) the COM stability at LO, (g) the COM position at the recovery step touchdown (TD), (h) the COM velocity at TD, and (i) the COM stability at TD. Both the COM position and velocity are relative to the rear edge of the base of support (BOS) and respectively normalized by foot length (l_{BOS}) and $\sqrt{g \times bh}$, where *g* represents the gravitational acceleration and *bh* the body height. Stability was calculated as the shortest distance from the given COM motion state to the threshold against backward balance loss (Fig. 1). 0: the barefoot group; 5: the thin sole group with 5-mm soles, and 10: the thick group with 10-mm soles.

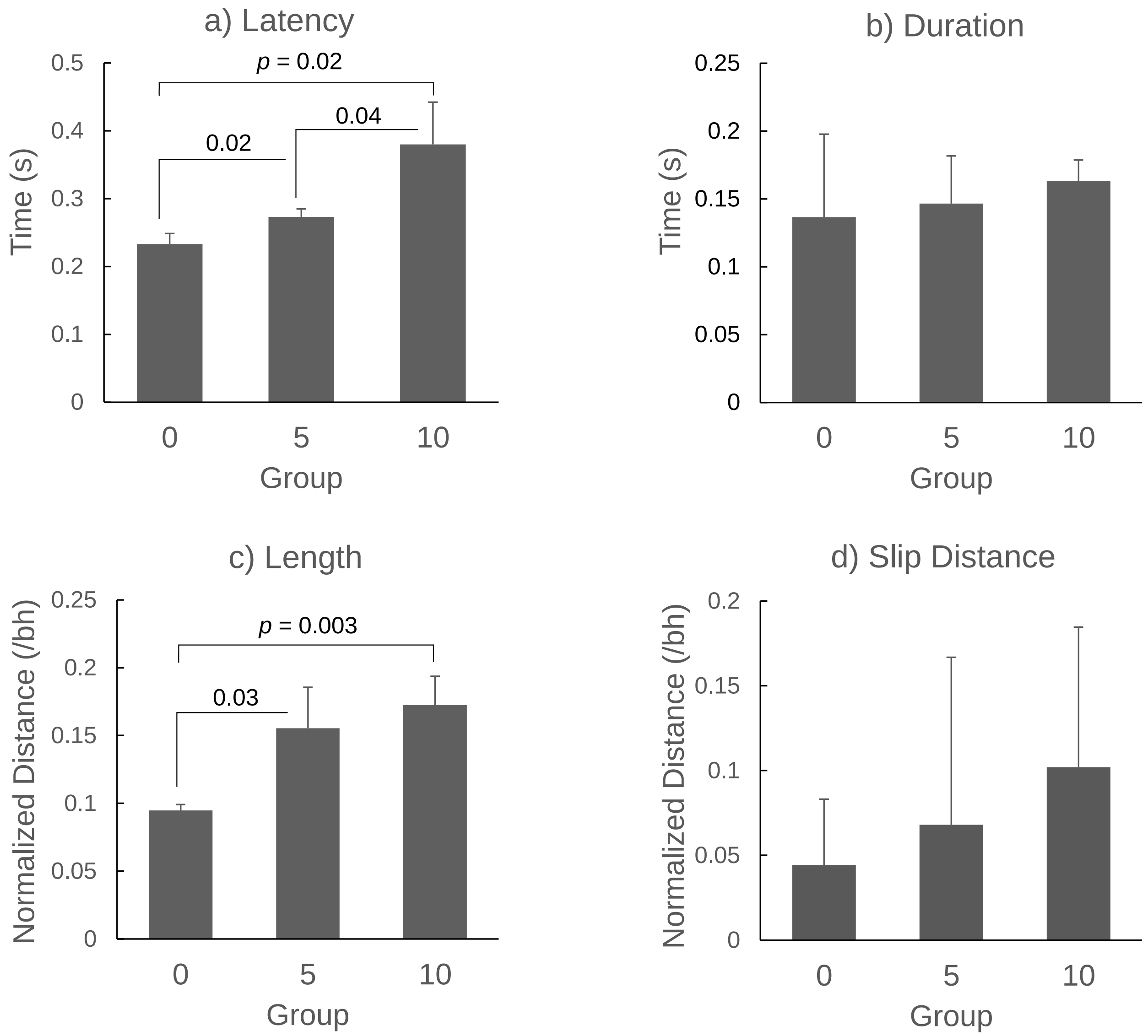


Figure 8. Comparisons of (a) latency, (b) duration, (c) length, and (d) slip distance of the recovery step in response to an unexpected stance-slip among the three groups: barefoot (0 mm), thin (5 mm), and thick (10 mm).

EMG Analysis

Overall EMG analysis revealed no statistical group difference. Specifically, there was no significant difference among groups in the EMG latency in both TA and GA ($p = 0.85$, $p = 0.33$

respectively, Fig. 9a, 9b). EMG burst also showed non-significance in group difference in TA and GA (*p* = 0.34, *p* = 0.42, Fig. 9c, 9d).

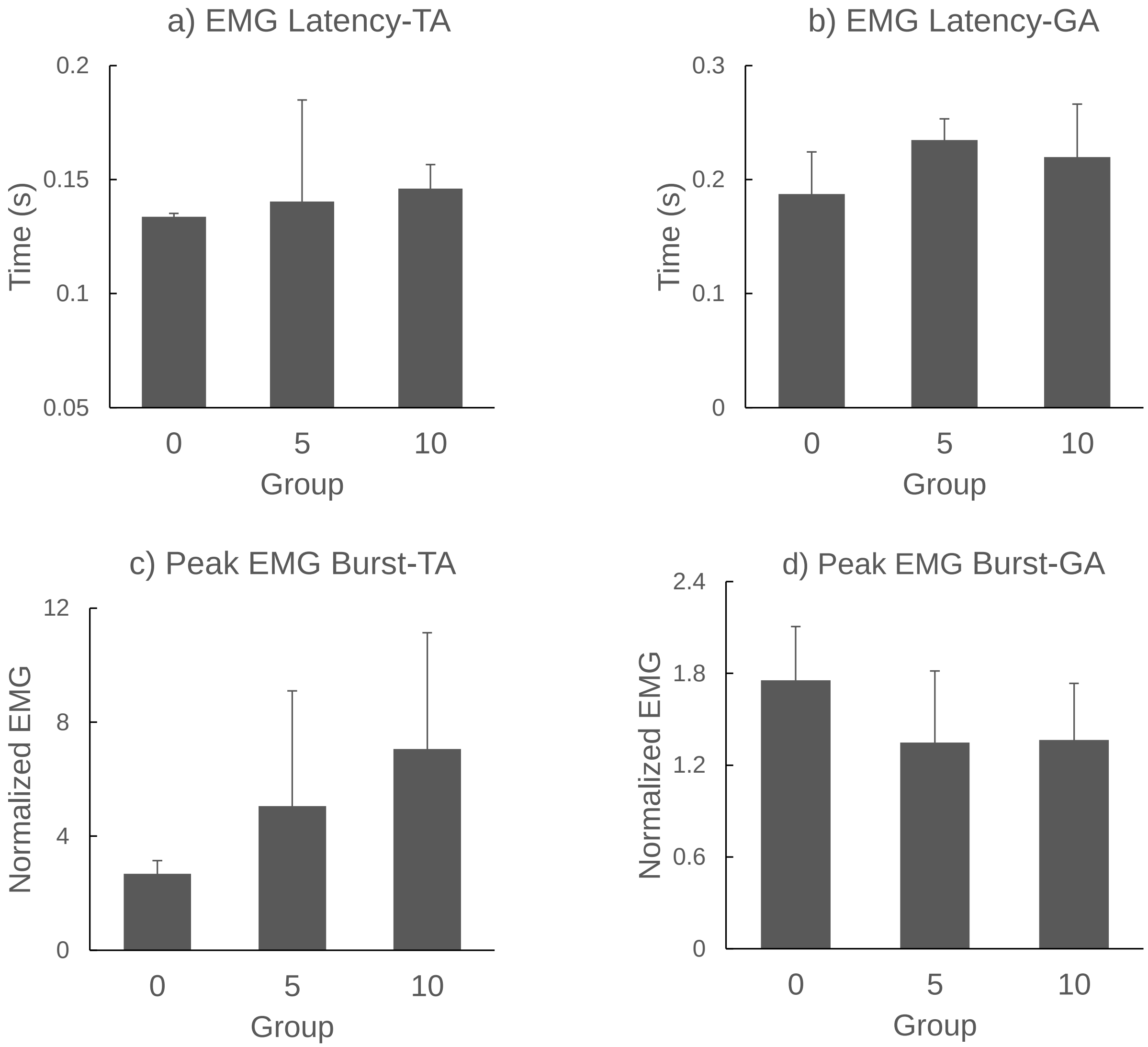


Figure 9. Comparisons of the EMG signal latency of the first recovery step in (a) tibialis anterior and (b) gastrocnemius, and the EMG burst of the first recovery step during slip normalized by the EMG signal during normal gait in (d) tibialis anterior and (d) gastrocnemius in response to an unexpected stance-slip among groups: barefoot (0 mm), thin (5 mm), and thick (10 mm).

Discussion

Although there is an agreement in the literature that the thick sole impairs body's balance and increases the risk of fall, the previous studies lack clear evidence which proves exactly how the thick soles explain the balance disturbance and the elevation of the fall risk on a biomechanical basis. Current study adopted novel variables and highly controlled experimental environment to verify the mechanical properties of the sole thickness as a key risk factor for falls and provide the standards to design and select the proper footwear in terms of the fall prevention for the population with elevated fall risk.

The purpose of this study was to demonstrate the impacts of the sole thickness impacts the risk of falls after an unexpected slip during standing among healthy young adults. The main findings of the current study were:

1. Thick sole impairs the dynamic gait stability and places the COM position relative to the BOS more posterior compared to the barefoot condition.
2. Thick sole delays the initiation of the recovery step after a slip-related perturbation and increase the recovery step length.
3. Increase in sole thickness merely affects the muscle activation patterns such as muscle latency and maximum muscle activation burst.

The results partially supported our first hypothesis that the thick soles would impair dynamic stability following an unexpected slip perturbation. In detail, people in the thick groups were less stable than those in the thin groups at LO, but not TD (Fig. 7f, 7i). The results confirmed that a thick sole could hinder the body's reactions to an unexpected slip perturbation.

Specifically, the thicker the sole, the longer the step latency, indicating that more time is needed to sense the perturbation and to plan the recovery step. The aftereffects of the same slip perturbation become more intense as sole thickness increases due to the increasingly delayed initiation of the recovery step, making the body more instable. This explained that the thin groups showed better dynamic stability than the thick groups at LO. However, at TD, all groups seemingly were able to successfully reestablish the BOS by taking an effective recovery step. As a result, all groups were similarly stable at TD.

The results about the spatiotemporal parameters also in part supported our second hypotheses which stated that a prolonged recovery step latency, a reduced recovery step duration, a shorter recovery step length, and a longer slip distance would be observed among groups with thicker soles than groups with thinner soles. Specifically, the step latency was shorter in the thin groups than in the thick groups (Fig. 8a) as expected; but the step length was longer in the thick groups than in the thin groups (Fig. 8c), indicating that the thick groups took a larger recovery step. Even though there was no group difference in the step duration, the step duration exhibited an increasing trend as sole gets thicker (Fig. 8b). It appears that the thick groups actually spent more time to complete the recovery step than the thin groups. As timely reactions are critical for one to reestablish balance and reduce the chance of falling, thick soles could increase one's risk of falls should an external perturbation occur due to the delay in sensing the perturbation. To arrest the backward falling trunk induced by the slip, individuals with thicker soles must take a greater recovery step to regain the body's balance as the level of the disturbance from the same slip perturbation in the thick groups was more severe than in the thin groups. To take a larger step, a longer duration is needed to execute the stepping process. In addition, although the slip distance did not differ significantly among groups, another trend emerges that the slip distance increases as the sole becomes thicker (Fig. 8d). Faster exertion of the recovery step in thinner groups could have reduced the distance of which the people slipped triggered by the perturbation.

Our third hypothesis was that the groups with thicker soles would display a longer EMG latency and greater EMG burst. This hypothesis was also not supported by the EMG analysis (Fig. 9). Despite of no statistical significance, there were several tendencies in accordance with the variation of the sole thickness. For example, the EMG latency was found to be prolonged with the thicker soles in the TA (Fig. 9a), which indicates that the TA muscle was activated later in the thicker groups than the thinner groups. Tang et al. (1998) found that the TA was triggered faster than the other extremity muscles to react to a slip and restore displaced ankle joint position. Sakai et al. (2008) drew the same conclusion that the TA latency was shorter than other muscles such as the BF. In current study, the thinner groups appeared to detect the slip initiation earlier than the thick groups, thus were able to activate the TA faster as an attempt to restore the displacement of the perturbed limb from the slip. The similar appearances of the latencies in the recovery step and EMG signal could be shared with our assumption that thick sole interrupts delivery of sensation from the plantar surface to the central nervous system and successively delays the reactional movement to the perturbation. The GA did not follow the same trend of the TA, but the EMG latency was the shortest in the barefoot group and longer in the thin and thick groups (Fig. 9b). This could reflect the same mechanism in the TA that the GA was also fired in response to the slip in the barefoot group in advance to the thin and thick groups as a result of earlier detection of the perturbation.

The EMG burst was adopted in this study to observe how strong the muscle force is exerted when our body experiences sudden and unexpected slip perturbation compared to the normal walking condition. According to our results, the normalized EMG burst in the TA were 2.68, 5.06, and 7.06 unit in the barefoot, thin, and thick sole group respectively, with an increasing pattern corresponding to the rise of the thickness of the sole (Fig. 9c). This could be interpreted that the TA was activated 7.06 times as they walk normally with thick sole, while only 2.68 times of force of normal gait was exerted on the TA with the barefoot condition. Tang et al. (1998) concluded that the TA is recruited more intensively than the other muscles to regain the disrupted ankle joint position and readjust the lower limb alignment. In other words, the greater amount of muscle activation after a slip implies the more amount of work done by the muscle to reestablish the joint position dislocated by the perturbation. In our study, the thicker the sole, the greater the intensity of the slip a participant experienced, thus the larger the amount of muscle force needed to react to the perturbation and recover from the balance loss. On the other hand, the GA muscle showed the opposite pattern of the EMG burst decreasing while the sole gets thicker (Fig. 9d). According to Tang et al. (1998), the GA is not much activated as the TA after a slip, rather it is inhibited, because the nervous system focuses on stimulating the TA which plays more important role to take reactional movements. Considering that there is no previous study which looked at the difference of the GA activation between conditions of different sole thicknesses, it is difficult to compare our results to the others to identify how the sole thickness interfere the fire of the GA. Further studies should be conducted to figure out whether the decreasing EMG latency in the GA is significantly related to the increasing sole thickness.

Given that the sole thickness has drawn attention in the literature as one of the major fall risk factors among mechanical properties of the shoes, its exact effects should apparently be investigated. There have been several previous studies that attempted to examine the relationship between sole thickness and risk of falls, but no study has brought the conclusion with precise examination of biomechanical variables with highly controlled design and circumstance. The observations in this study could enhance our understanding that the thicker soles negatively affect balance reconstruction after a slip perturbation by providing information of dynamic stability, spatiotemporal parameters, and muscle activity. This knowledge could be applied to establish the guidelines for the slip-resistant footwear design or fall prevention training protocol for the population with elevated risk of falls to stabilize their body when they encounter a slip-like perturbation.

Future Directions

The participant recruitment was interrupted by the ongoing pandemic. We were unable to enroll more subjects into this study. However, the data from the current nine participants (or 3 per group) provides me a meaningful dataset to conduct a power analysis to identify the required sample size which can verify our hypotheses with enough statistical power. Power analysis was tested with the dynamic stability as the primary outcome measure. Specifically, we used the value of stability at LO to estimate the required number of participants. The estimated effect size reported by the ANOVA was: 0.653 (η^2). With an α level of 0.05 and a statistical power of 0.80, the software of G*Power (Faul et al., 2007) indicated that nine subjects per group are needed.

There are several other possible directions for this project. First, future research should adopt a broader range of the sole thickness. Current study used only three conditions of the sole thickness: barefoot (0 mm), thin (5 mm), and thick (10 mm). Considering that there is no standard for the thickness of the sole to be ‘thick’ or ‘thin’ in the literature, there is a need to explore various thicknesses of the sole to comprehensively define the effect of the sole thickness on balancing process. Furthermore, a large number of subjects should be recruited in the prospective study to inspect the parameters with statistical non-significance in this study. As indicated by our power analysis, at least nine participants per group are needed to test whether the favorable trends in the spatiotemporal and EMG parameters show a statistically significant difference between groups.

Conclusion

The purpose of this study was to examine the effects of the sole thickness on the risk of falls after an unexpected slip perturbation during standing among young healthy adults. This study expands our understanding of reactional process to an unexpected stance-slip perturbation associated with the variation of the thickness of the shoe sole. The findings in current study includes that the thicker soles produce instable balance status with posterior COM position at the initiation of the recovery step, changes in spatiotemporal parameters such as a prolonged step latency and duration and larger step length, and a shorter EMG latency and lower EMG burst in TA and GA. This could provide an insight for designing and choosing the footwear for the population with elevated fall risk regarding the fall prevention. In addition, the information about biomechanical function of the sole thickness would advance the quality of fall prevention training to prevent fall-related outcomes such as minor to severe injuries and deaths.

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Appendix

Individual Values of Dynamic Stability at Different Events for All Groups

a-1. Dynamic stability at slip onset (ON) in group A (barefoot)

	COM position ($X_{COM/BOS}/l_{BOS}$)	COM velocity ($X_{COM/BOS}/(g \times bh)^{1/2}$)	Dynamic stability
Subject 1	0.289	-0.011	0.136
Subject 2	0.252	-0.012	0.116
Subject 3	0.349	-0.011	0.166

COM: center of mass, BOS: base of support, g: gravitational acceleration, bh: body height

a-2. Dynamic stability at slip onset (ON) in group B (5 mm)

	COM position ($X_{COM/BOS}/l_{BOS}$)	COM velocity ($X_{COM/BOS}/(g \times bh)^{1/2}$)	Dynamic stability
Subject 1	0.351	-0.005	0.172
Subject 2	0.304	-0.011	0.144
Subject 3	0.322	-0.014	0.149

COM: center of mass, BOS: base of support, g: gravitational acceleration, bh: body height

a-3. Dynamic stability at slip onset (ON) in group C (10 mm)

	COM position ($X_{COM/BOS}/l_{BOS}$)	COM velocity ($X_{COM/BOS}/(g \times bh)^{1/2}$)	Dynamic stability
Subject 1	0.436	-0.016	0.206
Subject 2	0.243	-0.008	0.115
Subject 3	0.383	-0.012	0.182

COM: center of mass, BOS: base of support, g: gravitational acceleration, bh: body height

a-4. Dynamic stability at liftoff (LO) in group A (barefoot)

	COM position ($X_{COM/BOS}/l_{BOS}$)	COM velocity ($X_{COM/BOS}/(g \times bh)^{1/2}$)	Dynamic stability
Subject 1	-0.184	-0.091	-0.187
Subject 2	-0.805	-0.205	-0.575
Subject 3	-0.797	-0.196	-0.564

COM: center of mass, BOS: base of support, g: gravitational acceleration, bh: body height a-5. Dynamic stability at liftoff (LO) in group B (5 mm)

	COM position ($X_{COM/BOS}/l_{BOS}$)	COM velocity ($X_{COM/BOS}/(g\times bh)^{1/2}$)	Dynamic stability
Subject 1	-0.193	-0.076	-0.18
Subject 2	-0.414	-0.161	-0.373
Subject 3	-0.185	-0.062	-0.165

COM: center of mass, BOS: base of support, g: gravitational acceleration, bh: body height

a-6. Dynamic stability at liftoff (LO) in group C (10 mm)

	COM position ($X_{COM/BOS}/l_{BOS}$)	COM velocity ($X_{COM/BOS}/(g\times bh)^{1/2}$)	Dynamic stability
Subject 1	-0.963	-0.262	-0.682
Subject 2	-0.72	0.006	-0.347
Subject 3	-0.375	-0.135	-0.331

COM: center of mass, BOS: base of support, g: gravitational acceleration, bh: body height

a-7. Dynamic stability at touchdown (TD) in group A (barefoot)

	COM position ($X_{COM/BOS}/l_{BOS}$)	COM velocity ($X_{COM/BOS}/(g\times bh)^{1/2}$)	Dynamic stability
Subject 1	-0.079	-0.169	-0.185
Subject 2	0.733	0.242	0.582
Subject 3	1.34	0.05	0.636

COM: center of mass, BOS: base of support, g: gravitational acceleration, bh: body height

a-8. Dynamic stability at touchdown (TD) in group B (5 mm)

	COM position ($X_{COM/BOS}/l_{BOS}$)	COM velocity ($X_{COM/BOS}/(g\times bh)^{1/2}$)	Dynamic stability
Subject 1	0.111	-0.031	0.029
Subject 2	0.519	0.025	0.286
Subject 3	-0.119	-0.103	-0.155

COM: center of mass, BOS: base of support, g: gravitational acceleration, bh: body height a-9. Dynamic stability at touchdown (TD) in group C (10 mm)

	COM position ($X_{COM/BOS}/l_{BOS}$)	COM velocity ($X_{COM/BOS}/(g\times bh)^{1/2}$)	Dynamic stability
Subject 1	1.205	0.042	0.594
Subject 2	-0.324	0.04	-0.155
Subject 3	0.615	0.105	0.404

COM: center of mass, BOS: base of support, g: gravitational acceleration, bh: body height

Individual Values of Spatiotemporal Parameters for All Groups

b-1. Spatiotemporal parameters in group A (barefoot)

	Step latency (s)	Step duration (s)	Step length (m/bh)	Slip duration (m/bh)
Subject 1	0.25	0.15	0.09	0.084
Subject 2	0.22	0.19	0.095	0.089
Subject 3	0.23	0.07	0.099	0.096

s: seconds, m: meters, bh: body height

b-2. Spatiotemporal parameters in group B (5 mm)

	Step latency (s)	Step duration (s)	Step length (m/bh)	Slip duration (m/bh)
Subject 1	0.28	0.15	0.142	0.12
Subject 2	0.28	0.18	0.19	0.189
Subject 3	0.26	0.11	0.134	0.125

s: seconds, m: meters, bh: body height

b-3. Spatiotemporal parameters in group C (10 mm)

	Step latency (s)	Step duration (s)	Step length (m/bh)	Slip duration (m/bh)
Subject 1	0.43	0.16	0.161	0.131
Subject 2	0.4	0.15	0.159	0.235
Subject 3	0.31	0.18	0.197	0.192

s: seconds, m: meters, bh: body height

Individual Values of EMG Analysis at Different Muscles for All Groups

c-1. EMG analysis in TA in group A (barefoot)

	EMG latency (s)	EMG burst
Subject 1	0.132	2.603
Subject 2	0.135	2.254
Subject 3	0.134	3.18

s: seconds

c-2. EMG analysis in TA in group B (5 mm)

	EMG latency (s)	EMG burst
Subject 1	0.191	9.679
Subject 2	0.107	2.222
Subject 3	0.123	3.265

s: seconds

c-3. EMG analysis in TA in group C (10 mm)

	EMG latency (s)	EMG burst
Subject 1	0.15	11.617
Subject 2	0.154	5.817
Subject 3	0.134	3.744

s: seconds

c-4. EMG analysis in GA in group A (barefoot)

	EMG latency (s)	EMG burst
Subject 1	0.227	1.475
Subject 2	0.154	2.149
Subject 3	0.181	1.639

s: seconds

c-5. EMG analysis in GA in group B (5 mm)

	EMG latency (s)	EMG burst
Subject 1	0.256	0.958
Subject 2	0.222	1.866
Subject 3	0.226	1.22

s: seconds

c-6. EMG analysis in GA in group C (10 mm)

	EMG latency (s)	EMG burst
Subject 1	0.222	0.948
Subject 2	0.172	1.5
Subject 3	0.265	1.648

s: seconds