ALTERNATIVE MEASURES OF TOE TRAJECTORY MORE ACCURATELY PREDICT THE PROBABILITY OF TRIPPING THAN MINIMUM TOE CLEARANCE

A Thesis

by

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ABSTRACT

Tripping is responsible for a large percentage of falls. Minimum toe clearance (MTC) during the swing phase of gait is commonly used to infer the probability of tripping (POT). However, there is limited empirical evidence to support the relationship between these two variables, and other measures of toe trajectory may better predict POT than MTC. The goals of this study were to: 1) quantify the relationship between MTC and POT; and 2) explore alternative measures of toe trajectory that may predict POT more accurately than MTC.

POT was estimated by comparing the distribution of obstacles measured along heavily-used, paved sidewalks on a university campus to the toe trajectory of 40 young adults obtained while walking over an obstacle-free walkway in a research laboratory. POT exhibited a curvilinear relationship with MTC, and regression equations were established to predict POT from MTC. POT was more accurately predicted when using virtual points on the bottom of the anterior edge of the shoe to determine MTC, compared to using a physical marker located on top of the toes to determine MTC. POT was also more accurately predicted when using a new measure of toe trajectory (the area below 40mm and above the toe trajectory, normalized by the swing length), compared to just MTC. These are the first empirical results supporting a relationship between MTC and POT. These results may improve the ability to identify risk factors that influence POT, and aid in developing interventions to reduce POT.

To my parents. For everything.

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Contributors

Part 1, faculty committee recognition

This work was supervised by a thesis committee consisting of Professor Michael Madigan (advisor) and Professor Roozbeh Jafari of the Department of Biomedical Engineering and Professor Pilwon Hur of the Department of Mechanical Engineering

Part 2, student/collaborator contributions

All work for the thesis was completed by the student, in collaboration with Professor Michael Madigan of the Department of Biomedical Engineering at Texas A&M University, and Professor Maury Nussbaum of the Department of Industrial and Systems Engineering at Virginia Tech.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Falls-related injuries levy a significant heath and economic toll on the United States. Unintentional falls are the single largest cause of non-fatal injury in people over the age of 65 in the U.S., with nearly 2.5 million injuries occurring annually (Centers for Disease Control and Prevention, 2013). Falls among older adults frequently result in moderate to severe injury and even death (Alexander et al., 1992). Post hospitalization, 43% of older adults that suffer fall-related injuries may be discharged to a nursing facility resulting in a loss of independence. Other long-term consequences include loss of confidence, increased susceptibility to future falls and decreased life expectancy. Non-fatal fall-related injuries in older adults result in direct medical costs of $31.3 billion to the United States (Burns et al., 2016). Fatal fall-related injuries cost the United States $637.2 million.

In the workplace, falls are also a significant source of fatal and non-fatal injuries. Of the 4,679 fatal occupational injuries in 2014, 17% (793) were caused by “falls, slips and trips” which was the second largest source of workplace fatalities behind transportation incidents (Bureau of Labor Statistics, 2015a). Among non-fatal injuries “falls on same level” and “falls to lower level” rank second and third, respectively, among the top sources of costs from disabling injuries, costing the United States $15.6 billion in direct workers compensation costs, which is 25% of the national burden (Liberty Mutual Research Institute for Safety, 2016). Over 300,000 non-fatal fall-related injuries that require days away from work occur each year in the United States (Bureau of Labor Statistics, 2015b). In addition to the direct costs, these injuries result in lost productivity from a median of 11 days away from work per injury, and reduced worker morale (Bureau of Labor Statistics, 2015b; Liberty Mutual Research Institute for Safety, 2007).

Trip-related falls

Tripping occurs when foot motion during the swing phase of gait is impeded by an obstacle or an abrupt change in elevation of the walking surface (Eng et al., 1994). The swing phase of gait occurs when the limb is unloaded and swings forwards towards the next foot placement (DeLisa, 2000). Encountering an obstacle during this phase arrests lower body motion while the upper body with its substantial inertia continues its forward motion (Grabiner et al., 1996). This causes a rotation of the trunk about the hips and the whole body about the tripping obstacle which if unchecked will cause a fall (Grabiner et al., 1993).

Trips account for a large proportion of falls among older adults. In a study of 1,042 adults above the age of 65 in the United Kingdom, Blake et al. report that 54% of all falls were caused by trips (Blake et al., 1988). In the U.S., a study on 96 adults above the age of 60 reported 34% of falls attributable to tripping (Berg et al., 1997). Trips are also a major cause of hip fractures. In their study of a 123 patients admitted for femoral neck fractures, Nyberg et al. found that trips caused 13% of these hip fractures (Nyberg et al., 1996). In a larger study on 787 hip fracture patients, Parker et al. report 22% of hip fractures to be caused by trips (Parker et al., 1996).

Trips also account for a large proportion of falls in the workplace. Among workers at a manufacturing facility, trips were responsible for 32% of the 226 recorded slips, trips and falls (Amandus et al., 2012). Among healthcare workers, trips caused 32% of falls and have been known to cause wrist fractures, rib fractures and ankle sprains (Liberty Mutual Research Institute for Safety, 2007). Among construction workers, trips have been reported to account for 23% of falls (Lipscomb et al., 2006). Injuries from trip-related falls in the workplace frequently require surgeries, lost days of work, and days of restricted work (Cappell, 2010; Liberty Mutual Research Institute for Safety, 2007).

Given the significant number of trip-related falls, preventing them is of major importance. The higher number of trip-related falls among older adults could be due to a higher frequency of tripping, a compromised ability to recover balance and prevent a fall after tripping, or both. Pavol et al. report that the number of trip related falls is governed chiefly by the frequency of trip events (Pavol et al., 1999). This study measured the kinematics of normal gait in 79 older adults, and then subjected them to a trip using a pneumatically-actuated mechanical obstacle that obstructed a foot during the swing phase. In examining the gait characteristics of subjects who fell after tripping vs. subjects that did not, faster gait speed, shorter step time and increased step length were found to be associated with an increased likelihood of falling after tripping. This suggests that walking more slowly improves the likelihood of recovering balance after tripping. This appears to contradict epidemiological studies reporting an association between slower walking speed, longer step times and decreased step length and a higher risk of trip-related falls (Imms and Edholm, 1981; Koski et al., 1996; Lipsitz et al., 1991; Lord et al., 1996; Nevitt et al., 1989; Wolfson et al., 1990; Woolley et al., 1997). A trip-related fall requires both the occurrence of a trip event and a failure to recover. Given that older adults have an increased risk of trip-related falls in spite of walking slower with longer step times and shorter step lengths, the gait characteristics associated with decreasing the frequency of tripping must be opposite to the characteristics associated with an increased ability to recover balance after tripping. The researchers thus conclude that the prevalence of trip-related falls in older adults is primarily determined by the frequency of tripping incidents. Given this result, determining factors that govern the probability of tripping (POT) is of major significance.

Minimum toe clearance to infer probability of tripping

Minimum toe clearance (MTC) is a frequently used indirect estimate of POT. MTC is determined from the toe trajectory during swing, and is the lowest height of the shoe/toe above the walking surface near mid-swing (Winter et al., 1990). When considering gait over multiple steps, it is generally accepted that a decrease in mean/median MTC, or an increase in MTC variability, indicates an increase in POT on account of reduced clearance over obstacles or abrupt changes in elevation (Barrett et al., 2010; Begg et al., 2007). Given this, studies have investigated the effects of a range of intrinsic factors (e.g. age, sex, obesity), extrinsic factors (e.g. floor surface, footwear), and task-related factors (e.g. gait speed, load carriage) on MTC in an effort to identify factors contributing to trip-induced falls.

Age has been shown to influence MTC, although the effects are not consistent across studies. Begg et al. reported no significant difference in MTC central tendency (mean and median) between their samples of 17 young (age: 26 ± 5 years) women and 16 older (age: 72 ± 4 years) women (Begg et al., 2007). Mills et al. also report no significant difference in median MTC between their groups of 10 young (age: 26 ± 3 years) and 9 older (age: 71 ± 3 years) men (Mills et al., 2008). Garman et al. in a sex, age and BMI balanced study of 80 participants report no significant effect of age on median MTC in both obese and normal-weight groups (Garman et al., 2015). Menant et al. however, in their study on 10 young (age: 27 ± 3 years) and 26 older (age: 79 ± 4 years) *did* find a significant increase in MTC among older adults (Menant et al., 2009). Begg et al. report significantly larger variability in MTC (standard deviation (SD) and interquartile range (IQR)) among older adults, a finding matched by Mills et al. who examined MTC IQR (Begg et al., 2007; Mills et al., 2008). Garman et al. however report no significant effects of age on MTC IQR among both obese and non-obese adults (Garman et al., 2015). They also report no significant effects of obesity on both median MTC and MTC IQR. Significant differences were however found for sex in both median MTC and MTC IQR with females exhibiting lower MTC and smaller variability.

Extrinsic factors have also been shown to influence MTC. Irregular walking surfaces have been shown to increase MTC, with older adults showing greater clearance on these surfaces than young subjects (Menant et al., 2009). Thies et al. also report higher MTC over tactile paving of the kind used for the visually impaired, suggesting that subjects perceive an increased POT and compensate by increasing MTC (Thies et al., 2011). Surface inclination also affects MTC with both declines and inclines causing an increase in MTC (Thies et al., 2015, 2011). Footwear also influences MTC. For example, slippers cause a decrease in MTC when compared to well-fitted shoes, implying a higher POT (Davis et al., 2016). Increasing the angle of the shoe sole to the ground at the toe region of the shoe (rocker angle) has been shown to increase MTC (Thies et al., 2015, 2011). High heeled shoes can also increase MTC, a possible reaction to a perceived increase in POT, while high-top shoes have the opposite effect on MTC, which may be a consequence of reduced ankle mobility and dorsiflexion during swing.

Limitations of using minimum toe clearance to infer probability of tripping

Despite the wide acceptance of using MTC to infer POT, there is limited empirical evidence on the relationship between MTC and trip-induced falls. Three studies to our knowledge have examined the relationship between MTC and retrospectively reported falls among older adults (Gehlsen and Whaley, 1990; Khandoker et al., 2008a, 2008b). Comparing 25 older adults with a history of falls in the previous 10 months to 30 with no history of falls, Gehlsen and Whaley report no significant difference in MTC between the two groups (Gehlsen and Whaley, 1990). Khandoker et al., in two separate studies, compared central tendency and variability of MTC between older adults with a history of fall and those without. Examining the mean, standard deviation and approximate entropy (a measure of variability in data) of MTC in 14 older adults without a history of falls and 10 with a reported fall in the previous year, measures of variability were significantly greater in the group with a history of falls while mean MTC was not significantly different (Khandoker et al., 2008a). The second study on data from 27 older adults without a history of falls and 10 with a reported fall in the previous year, found both measures of central tendency (mean and median) and measures of variability (SD and IQR) to be significantly larger in the group with a history of falls (Khandoker et al., 2008b). Given that increases in central tendency and variability of MTC are associated with lower and higher POT respectively, the difference in POT between these two groups was unclear. Of these three studies, only one reported significant differences in central tendency between fallers and non-fallers, and two reported significant differences in variability. Also, given that these studies use retrospectively reported falls, it is unclear if these differences in the fallers existed before the fall or presented as a reaction to the fall.

Two studies have used MTC to calculate POT. Garman et al. used MTC data from multiple walking trials, and compared these values to a range of obstacle heights ranging from 0–7cm to compute a POT for each obstacle height defined as the percentage of MTC values greater than the obstacle height. Using this measure to examine the effects of age, gender and obesity through a novel statistical bootstrapping method, significant effects of age and obesity were observed where median MTC and MTC IQR showed no significant difference. Females were shown to have a higher POT using this method, while median MTC and MTC IQR indicated opposite effects of sex on POT (Garman et al., 2015). Best and Begg describe a method of calculating POT using statistical modelling of MTC data. Using skewness and kurtosis to model the distribution of MTC, POT for a given obstacle height is calculated as the probability of occurrence of an MTC value lower than the obstacle height (Best and Begg, 2008). As acknowledged by the researchers this method assumes that the tripping obstacle is present at the same location as MTC while an unseen obstacle could be present anywhere in the swing phase. The method presented by Garman et al. also exhibits the same limitation.

Using MTC to infer POT is limited because MTC occurs at a single location over the swing phase, while an obstacle (and trip) could occur at any location in the swing phase. For example, foot/toe trajectories during swing could exhibit the same MTC but still differ substantially over other parts of the swing phase (Figure 1). Given the limitation of MTC, these trajectories would all be associated with the same POT. However, knowledge that a trip can occur at any point during swing would clearly result in differences in POT. As an example, adults with Down’s Syndrome are known to show flatter foot trajectories than adults without Down’s Syndrome (Smith and Ulrich, 2008). Using MTC to infer POT would underestimate the POT for these individuals as the foot is close to the ground for a larger portion of the swing phase. Measures of the foot trajectory that incorporate more of the available information and account for these flatter trajectories should provide better estimates of POT than MTC.

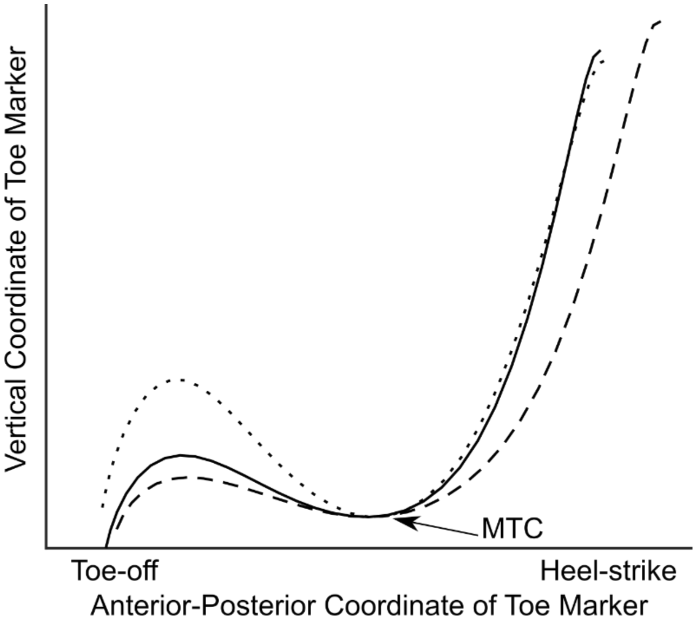

Figure 1. Three sample toe trajectories during the swing phase of gait that have identical MTC but exhibit variability in the rest of the swing phase. Examining MTC would indicate identical POT for all three trajectories but intuitively, these three trajectories should differ in POT, since a tripping obstacle with a height greater than the toe trajectory could be present at any point between toe-off and heel-strike.

The goals of the study presented here in this thesis are threefold. First, develop a method of calculating POT that incorporates the entire swing phase foot trajectory. Second, use this method of computing POT to determine the relationship between MTC and POT. Third, explore new metrics of foot trajectory that better predict POT than MTC.

This study would be, to our knowledge, the first to develop a method of calculating POT that incorporates the whole swing phase trajectory and does not assume the tripping obstacle to be present at MTC. It would also be the first to demonstrate the empirical relationship between POT and MTC.

The following chapter is a self-contained manuscript published in the *Journal of Biomechanics* that documents this work. As such, some redundancy exists between this current chapter and the next chapter.

CHAPTER II

ALTERNATIVE MEASURES OF TOE TRAJECTORY MORE ACCURATELY PREDICT THE PROBABILITY OF TRIPPING THAN MINIMUM TOE CLEARANCE[*]

Introduction

Tripping is responsible for 23-32% of falls among workers (Amandus et al., 2012; Lipscomb et al., 2006), and 35-53% of falls among older adults (Berg et al., 1997; Blake et al., 1988). Tripping occurs when foot motion during the swing phase of gait is impeded by an obstacle or an abrupt change in elevation of the walking surface. Researchers commonly use minimum toe clearance (MTC) during swing to infer the probability of tripping (POT) (Barrett et al., 2010; Garman et al., 2015; Schulz, 2011; Thies et al., 2015). MTC is determined from the toe trajectory during swing, and is the lowest height above the walking surface near mid-swing (Winter, 1991). It is generally accepted that a decrease in mean/median MTC, or an increase in MTC variability, infers an increase in POT due to less clearance over obstacles or abrupt changes in elevation (Barrett et al., 2010; Begg et al., 2007).

Despite the general acceptance of MTC as a measure to infer POT, there is limited empirical evidence to support this relationship. Only three studies, to our knowledge, have reported an association between MTC and retrospectively reported falls

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[*] Reprinted with permission from "Alternative measures of toe trajectory more accurately predict the probability of tripping than minimum toe clearance." by Achu G. Byju, Maury A. Nussbaum, and Michael L. Madigan, 2016. Journal of Biomechanics, doi: 10.1016/j.jbiomech.2016.10.045, Copyright 2016 by Achu G. Byju

(Gehlsen and Whaley, 1990; Khandoker et al., 2008a, 2008b). While two of three of these studies reported statistically significant differences in mean/median MTC (Khandoker et al., 2008b) or MTC variability (Khandoker et al., 2008a; Khandoker et al., 2008b) between fallers and non-fallers, no studies to our knowledge have demonstrated a quantitative predictive relationship between MTC and POT. In fact, it could be argued that MTC is limited in its ability to predict POT given that it only quantifies toe height at one instant during swing, though a trip obstacle could be present at any point during swing (Figure 2). A measure of toe trajectory that incorporates more of the swing phase toe trajectory may predict POT more accurately than MTC.

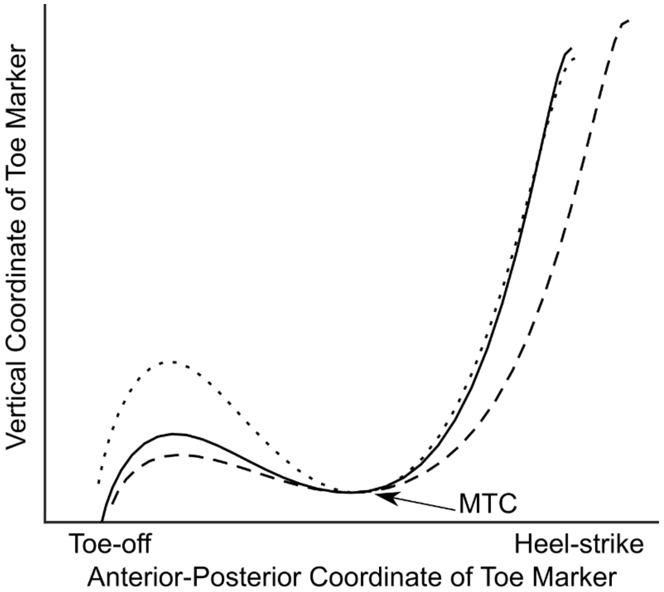

Figure 2. Three sample toe trajectories during the swing phase of gait, illustrating variability between swing trajectories during phases other than the point of MTC. Intuitively, these three trajectories should be associated with different probabilities of tripping, since a tripping obstacle with a height greater than the toe trajectory could be present at any point between toe-off and heel-strike. However, because all three trajectories exhibit the same MTC, all three would be considered to have the same probability of tripping.

The goals of this study were to: 1) quantify the relationship between MTC and POT; and 2) explore alternative measures of toe trajectory that may predict POT more accurately than MTC. Prior to addressing these goals, two intermediate steps were completed. First, we developed a method to calculate POT so that its relationship with MTC could be determined, and for use as a basis for comparison between alternative measures of toe trajectory. Second, we determined how the choice of location on the shoe used to determine toe trajectory, and hence MTC, influenced the accuracy of predicting POT. We hypothesized that: 1) the ability to predict POT from MTC would differ based upon the location on the shoe that was used to determine the toe trajectory; 2) measures of the toe trajectory that incorporated more of the swing phase would better predict POT than just MTC.

Methods

To estimate POT, it was necessary to obtain a realistic distribution of tripping obstacles. We measured the number and height of abrupt changes in elevation (not including intentional changes in elevation such as a curb) along 2.1 km (2,695 steps by AGB) of heavily-used, paved sidewalks on a university campus. These obstacles were measured using a 10-cm ruler positioned horizontally on top of the obstacle, and a second ruler positioned vertically and resting at the base of the obstacle (Figure 3). Obstacle height was then measured using the vertical ruler. Only obstacles ≥ 6 mm in height were recorded to be consistent with ASTM F1637 (2013), which is an accepted international safety standard specifying that abrupt changes in walkway elevation less than 6 mm do not require remediation (and implying an acceptably low potential to cause a trip).

Figure 3 Left: Front-view of a representative tripping obstacle measured on the Texas A&M University campus; Right: Side-view of the same obstacle illustrating obstacle height measurement with a pair of rulers

To estimate POT, it was also necessary to obtain toe trajectory data during gait. These data were obtained inside our research lab, rather than outdoors over the same sidewalk from which we measured obstacle heights, due to equipment limitations and difficulty determining toe height outdoors. Further, changes in gait due to visible obstacles (Begg et al., 2007; Schulz, 2011) and experiencing a trip (Pavol et al., 1999; Schulz, 2011) would limit generalization to natural gait without a recognized threat of a trip (when most trips are likely to occur).

Subjects involved in gait testing included 40 young adults (18-30 years; 20 men) without any self-reported conditions that affected their gait. The lab study was approved by the local Institutional Review Board, and all subjects provided informed consent prior to participating. Subjects wore the same model of low-top walking shoe (Levi's® Jeffrey Denim) with a flat sole and low rocker angle (Figure 4). Ten trials were completed during which subjects walked at a self-selected speed along a 10 m laboratory walkway. Reflective markers were attached bilaterally over the lateral malleoli, and on both shoes at the heel, toe, and lateral aspect (Figure 4). Marker positions were sampled at 100 Hz using an 8-camera motion capture system (Qualisys AB, Göteborg, Sweden), and low-pass filtered at 10 Hz (second-order Butterworth filter). One swing phase (i.e., toe off to heel strike, identified using the method of (Zeni et al., 2008) from each foot was isolated from each trial for analysis. Virtual markers along the bottom of the anterior edge of the shoe (Figure 4) were defined within a shoe-fixed coordinate system (Startzell and Cavanagh, 1999). Before walking trials began, subjects stood in the middle of the walkway, near where MTC was subsequently measured during the walking trials, and lightly touched the bottom of the anterior edge of the right shoe to the ground. The lowest vertical coordinate among the virtual markers on the right shoe during this trial established the level of the walkway surface. All data processing and computations for calculating POT (described below) were performed using custom code in Matlab (Mathworks, Inc., Natick, MA).

Figure 4. Photograph of the shoes worn by subjects showing the placement of physical markers and virtual markers. The positions of the virtual markers were defined within a shoe-fixed coordinate system defined using the three physical markers shown.

Three methods were used to generate three separate sagittal plane toe trajectories during swing. Investigating three methods allowed us to evaluate the potential trade-off between sophistication during data collection/processing, and the accuracy of POT predictions. The first toe trajectory was of the physical toe marker, and was considered the least sophisticated method of determining toe trajectory. The second toe trajectory was of the *single* anterior-most virtual marker on the shoe that was preselected before data collection, and was considered a moderate level of sophistication because it required using a shoe-fixed coordinate system to predict the position of a single virtual marker on the shoe. The third toe trajectory was of the *instantaneous* anterior-most virtual marker on the shoe within each sampled frame of marker data, and was considered the highest level of sophistication because it required using a shoe-fixed coordinate system to predict the position of multiple virtual markers and the need to determine the anterior-most of these virtual marker at each instant. MTC was defined as the minimum height of the trajectory after the first maximum in toe height (Nagano et al., 2011), and was identified using zero-crossings of the first derivative of the vertical coordinate of the trajectory. MTC was determined from each of the three trajectories, and yielded $MTC_{Physical}$, MTC_{Pre}, and $MTC_{Instant}$, respectively.

POT was determined for each swing phase using the toe trajectory of the instantaneous anterior-most virtual marker. First, the swing phase was segmented into 1 mm increments in the anterior-posterior direction. At each 1 mm increment, the distribution of obstacle heights was compared to the toe trajectory height, and the total number of trips that would have occurred was determined (a trip was assumed to have occurred if the obstacle height exceeded the vertical component of the toe trajectory). This process was repeated at each 1 mm increment throughout the trajectory. Second, POT was calculated as the quotient of the total number of trips and the total number of comparisons. From this, POT was the percentage of swing phases that would have resulted in a trip, given the distribution of obstacles that we measured over 2,695 steps. Scatterplots were generated between the three MTC values and POT to visualize these relationships. Transformations were explored in an attempt to find linear relationships between MTC and POT that most accurately predicted POT (as inferred by the smallest standard error of estimate: SEE), while also favoring models and transformations that resulted in reasonably uniform residuals.

Sixteen alternative measures of toe trajectory were also explored and compared in their ability to predict POT. These alternative measures were developed based upon intuition and a desire to include more of toe trajectory, and are listed and illustrated in the online supplementary material. The measure that exhibited the smallest SEE with reasonably uniform residuals was the area below a 40mm “threshold” and above the toe trajectory, normalized by the length (i.e. distance) of swing (Figure 5). This area represents the mean distance of the toe trajectory below 40 mm (MD40). All of these alterative measures used the toe trajectory of the instantaneous anterior-most virtual marker. As with MTC, transformations were explored for each alternative measure to find the linear relationship that best predicted POT (smallest SEE) with reasonably uniform residuals.

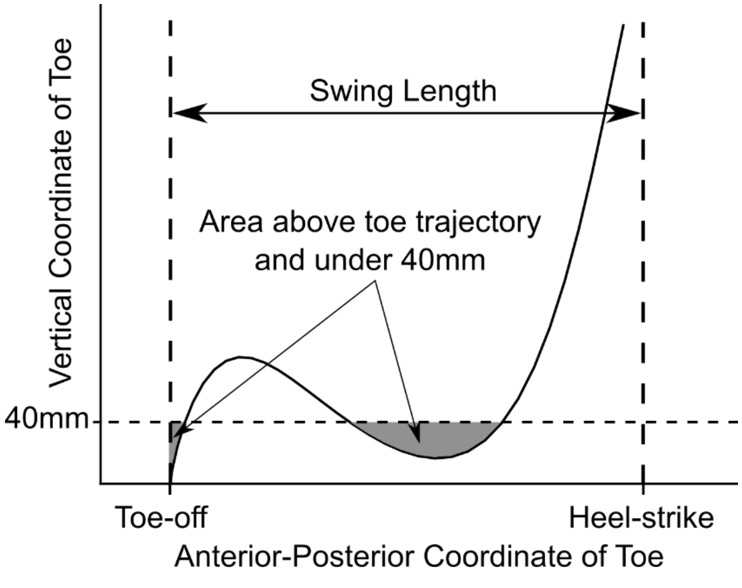

Figure 5. Schematic illustrating the calculation of the alternative measures that best predicted the probability of tripping. The alternative measure was calculated as the area below 40 mm and above the toe trajectory, divided by swing length.

Results

Thirty-five obstacles ranging in height from 6 to 29 mm were measured from the sidewalk, with a median (interquartile range) of 11 (11) mm (Figure 6). POT for each swing phase ranged from 0.2-0.8%, indicating that a trip is expected to occur once every 125-500 steps during natural gait (e.g., without any expectation of a trip) and given the measured distribution of obstacles. All three MTC values exhibited a curvilinear relationship with POT (Figure 7), and a cube-root transformation of POT resulted in the lowest SEE for the linear relationships we explored. Among the three MTC values, $MTC_{Instant}$ exhibited the lowest SEE (0.046%), while $MTC_{Physical}$ exhibited the highest SEE (0.085%) when predicting POT. $MTC_{Instant}$ across all subjects and all trials had a mean ± standard deviation of 12.8 ± 6.9 mm with a skewness of 0.81, and a median (interquartile range) of 11.7 (8.3) mm. Among the 16 alternative measures explored, MD40 most accurately predicted POT based upon an SEE of 0.029%, which was 37% lower than $MTC_{Instant}$, and the lowest of all alternative measures that exhibited reasonably uniform residuals (Figure 8 and supplementary material).

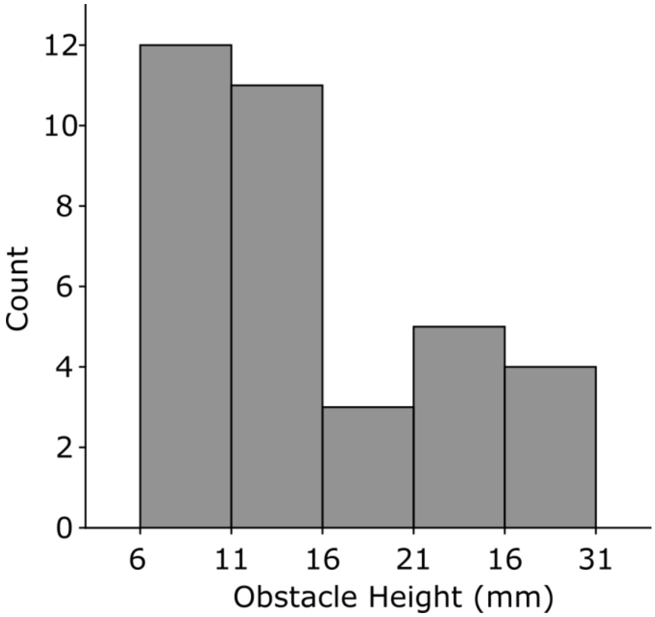

Figure 6. Distribution of tripping obstacles (abrupt changes in elevation) measured along 2,695 steps (i.e. 2.1 km) of heavily-used, paved sidewalks on a university campus. Obstacles with heights less than 6 mm were not included.

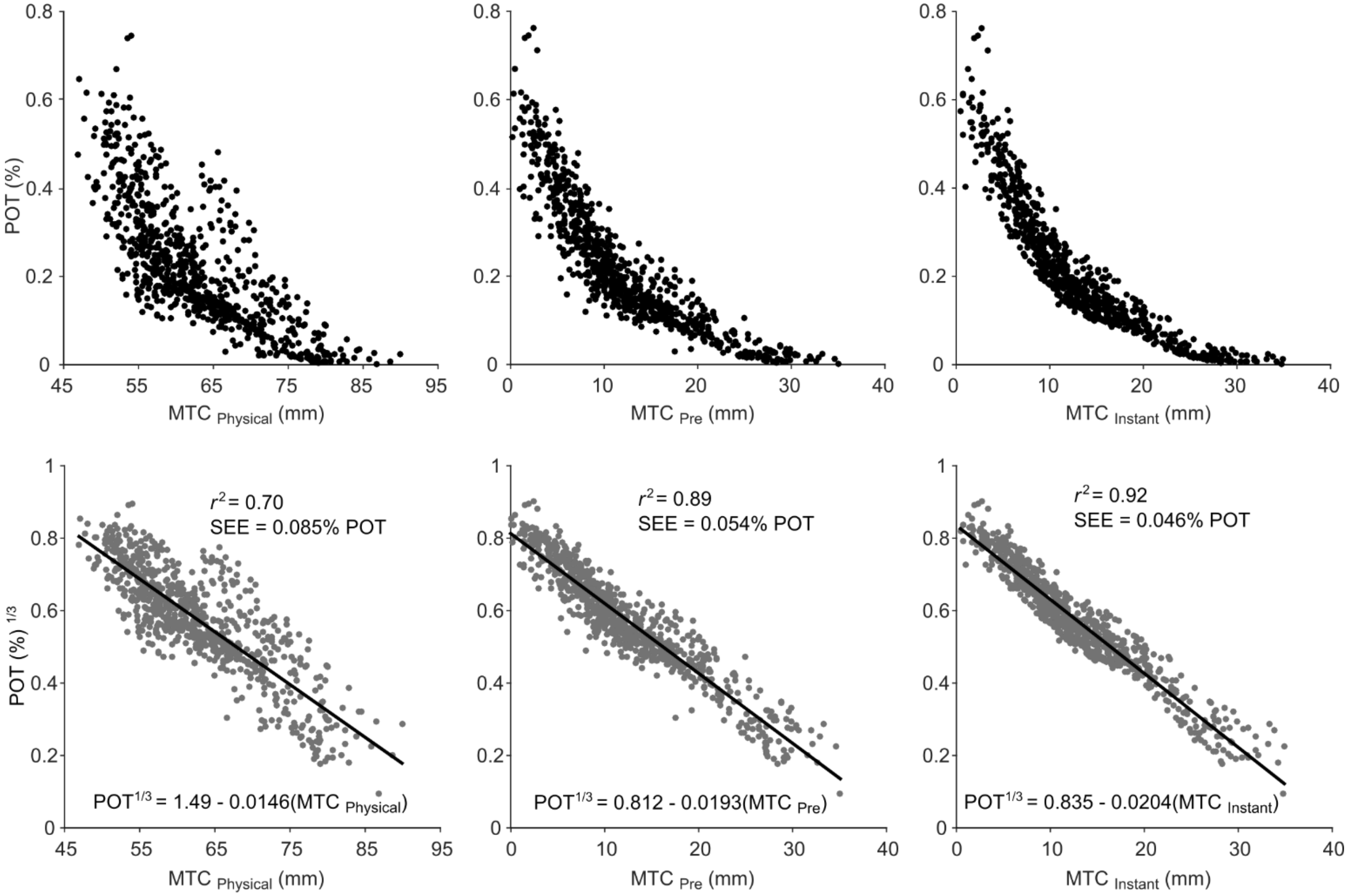

Figure 7. Scatterplots illustrating a curvilinear relationship between minimum toe clearance (MTC) and the probability of tripping (POT) (upper row), and regression lines used to predict the cube root of POT from MTC (lower row). When using these regression equations, MTC should be in units of mm, and the solution should be cubed to calculate POT (the percentage of swing phases that would have resulted in a trip, given the distribution of obstacles that we measured). The three columns illustrate differences in the accuracy of predictions when using MTC values derived from the three toe trajectories.

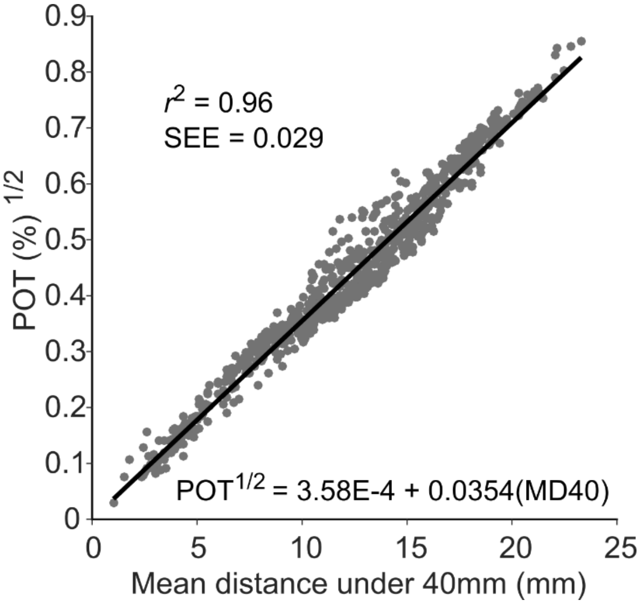

Figure 8. Scatterplot illustrating the relationship between MD40 (area below 40 mm and above toe trajectory, divided by swing length) and the probability of tripping (POT), including a regression line with necessary transform to achieve a linear relationship and lowest standard error of the estimate.

Discussion

The first goal of this study was to quantify the relationship between MTC and POT. Prior to addressing this goal, we determined how the choice of location on the shoe used to determine toe trajectory, and hence MTC, influenced the accuracy of predicting POT. We hypothesized that the ability to predict POT from MTC would differ based upon the location on the shoe that was used. Clear differences were evident (Figure 7), and the toe trajectory (and MTC) derived from the instantaneous anterior-most virtual marker exhibited the best accuracy when predicting POT. However, this method also required the highest level of sophistication during data collection and processing, given the need to predict the position of multiple (20 in this study) virtual markers on the shoe and to determine the most anterior marker at each frame of analysis. Using the preselected single anterior-most virtual marker on the shoe only increased SEE from 0.046 to 0.054% POT, and may thus be more efficient (needing only predictions of the position of a single virtual marker on the shoe). Both methods that used virtual markers along the bottom of the anterior edge of the shoe, however, more accurately predicted POT than using a physical marker placed above the toes. This was likely due to the fact that MTC_{Pre} and $MTC_{Instant}$ represent points on the shoe that are the most anterior and inferior on the shoe, and therefore most likely to impact a tripping obstacle. $MTC_{Physical}$ does not predict POT as accurately as these other two methods because the geometric relationship between this marker and the most anterior and inferior point on the shoe (most likely to impact a tripping obstacle), while constant in a shoe-fixed coordinate system, is variable in a global coordinate system, and depends upon the angles of joints in both the swing and stance lower limbs (Winter, 1992).

The second goal of this study was to explore alternative measures of toe trajectory that may predict POT more accurately than MTC. We hypothesized that measures of toe trajectory that incorporated more of the swing phase would better predict POT than just MTC. Supporting this hypothesis, MD40 predicted POT more accurately than MTC or any other alternative measure. The improved ability of MD40 at predicting POT, which includes the possibility of a trip occurring at any point within swing, was likely due to: 1) including more of the swing phase than just MTC; and 2) not including portions of the toe trajectory when its height is above 40 mm; such portions are inconsequential to POT because no obstacles were above 40 mm in the distribution of obstacles used to calculate POT. The area below a 30mm threshold and above the toe trajectory, normalized by the length of swing (i.e. MD30) exhibited a smaller SEE than MD40, but the residuals were not uniform indicating an undesirable variation in accuracy of prediction within the range of MTC investigated. Interestingly, the area under 40 mm and *under* the toe trajectory did not predict POT as accurately at MD40 (SEE = 0.085%; see supplementary material). This was likely because this area was larger than that in MD40, and was therefore less sensitive to small changes in toe trajectory below 40 mm than the area below 40 mm and above the toe trajectory. Future work involving different distributions of tripping obstacles may need to adjust this 40 mm threshold.

To accomplish the goals of this study, it was necessary to develop a method to calculate POT to serve as a basis of comparison for MTC and the alternative measures. Our method involved several assumptions and limitations. First, toe trajectory data used to estimate POT were obtained without the threat of an actual tripping obstacle. As such, the POT reported here is most relevant for unexpected and unseen tripping obstacles (when most trips are likely to occur). This implicit assumption is also common among studies that use MTC to infer POT. Second, POT was estimated by assuming that the tripping obstacle was equally likely to appear at any anterior-posterior location (within a 1 mm increment) throughout the swing phase. Given the lack of relevant quantitative data indicating otherwise, we considered this a reasonable assumption. Third, we only used the sagittal plane trajectory of the swing foot, and assume any obstacle would exist within this plane. Fourth, our method considered a trip to have occurred when an obstacle would have impacted the “leading edge” of the shoe, and not when an obstacle would have contacted or “scuffed” against the bottom sole of the shoe. While such scuffs could lead to forward falls similar to trips, we elected to not consider them due to greater difficulty in predicting the extent to which swing foot motion would be subsequently altered. Fifth, POT values, and the regression models that predict POT from MTC, are specific to the distribution of obstacle heights used to estimate POT. Sixth, we only explored linear relationships between alternative measures and POT (transformed or not transformed) for simplicity, but acknowledge that additional non-linear terms in the regression equation may provide small improvements in accuracy. Seventh, the POT values reported here were for young adults walking over a level surface at a self-selected speed. Care should thus be used when generalizing beyond these conditions and subjects. However, the methods reported here should generalize to other subject populations.

A logical alternative to our method of calculating POT would be to determine the number of steps and trips while subjects walked along the same outdoors sidewalk over which obstacles were measured. However, this seemingly straightforward approach involves substantial experimental limitations. First, normal variations in ground surface along the outdoor sidewalk (e.g. varying pitch and texture of walking surface) would make it difficult to quantify the height the toe trajectory accurately. Second, gait is altered after experiencing a trip (Pavol et al., 1999; Schulz, 2011). So if/when a subject experienced a trip, their results could no longer be generalized to typical (unexpected) trips. Third, gait is altered when tripping obstacles are visible (Begg et al., 2007; Schulz, 2011). So after a subject sighted an obstacle (the timing of which could differ between subjects), their results could no longer be generalized to unexpected trips. We thus used an approach that combined an obstacle-free walking surface without the threat of a trip, and a distribution of measured obstacles measured elsewhere, to provide a more robust method and results that are expected to better generalize to unexpected trips.

Best and Begg (2008) measured the toe trajectory of a subject walking on a treadmill and used statistical modeling to predict POT from MTC for a , *assuming a tripping obstacle was present at the same location as MTC* (Best and Begg, 2008). At an obstacle height of 1.2 cm (closest value reported by these authors to the mean $\text{MTC}_{\text{Instant}}$ of 1.28 cm found here), they predicted a trip to occur every 1.24 steps, or during 80.6% of steps. This method of calculating POT (assuming a tripping obstacle to be present at the same location as MTC) differed from our method, in that the POT we report represented the percentage of steps with identical toe trajectory that would have resulted in a trip over 2,695 steps (2.1 km of sidewalk), given the distribution of tripping obstacles measured (including steps with no obstacle). Our method also accounts for the possibility of a tripping obstacle to be presented at any point over the swing phase, not just at MTC. While both approaches to estimating POT are valuable, the current one incorporates the prevalence of tripping obstacles, and may thereby represent a more ecologically-valid estimation. When predicting POT from $\text{MTC}_{\text{Instant}} = 1.2$ cm, our method predicts a trip to occur during 0.21% of steps, or one trip every 476 steps. We are able to make a reasonable comparison between the POT reported from both studies if we multiply the 80.6% of steps reported by Best and Begg (2008) by the percentage of

2,695 steps that involved a tripping obstacle greater than 1.2 cm (13 steps out of 2,695 steps = 0.48%). This predicts a trip to occur during 0.39% of steps, or one trip every 256 steps, which is a POT of the same order of magnitude as that reported here. Some level of convergent validity is thus apparent between the two rather distinct approaches.

Conclusion

A method was developed to calculate POT during gait, and was used to determine the relationship between MTC and POT. POT was more accurately predicted when using virtual points on the bottom of the anterior edge of the shoe to determine MTC, compared to using a physical marker located on top of the toes to determine MTC. POT was also more accurately predicted when using a new measure of toe trajectory, compared to just MTC. Results from this work may help improve the accuracy of predictions of POT from toe trajectory, which can allow researchers and clinicians to better appreciate the clinical significance of alterations in MTC on POT. It may also improve the ability to identify risk factors that influence POT, and help develop interventions to reduce POT.

CHAPTER III

SUMMARY

A method of calculating POT from the swing phase toe trajectory was developed and used to examine the relationship between MTC and POT. MTC was found to exhibit a curvilinear relationship with POT. Using the trajectory of a virtual marker to calculate MTC resulted in a better prediction of POT than using the trajectory of the physical marker on top of the shoe. A new measure of foot trajectory was also developed that better predicted POT than MTC.

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