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Alternative measures of toe trajectory more accurately predict the probability of tripping than minimum toe clearance

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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 tripping 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 40 mm and above the toe trajectory, normalized by the swing length), compared to just MTC. These are the first empirical results supporting a direct, quantitative 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.

1. 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 (Gehlsen and Whaley, 1990; Khandoker et al., 2008a, 2008b). While two of three of these studies reported differences in mean/median MTC (Khandoker et al., 2008b) or MTC variability (Khandoker et al., 2008a, 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 (Fig. 1). A measure of toe trajectory that incorporates more of the swing phase toe trajectory may predict POT more accurately 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. 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

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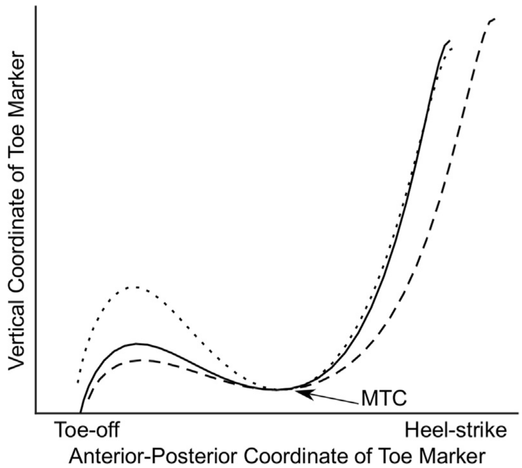

Fig. 1. Three sample toe trajectories during the swing phase of gait, illustrating variability between swing trajectories during phases other than the point of MTC. Intuitively, these three trajectories should be associated with different probabilities of tripping, since a tripping obstacle with a height 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.

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.

2. 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 (2695 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. Obstacle height was then measured using the vertical ruler. Only obstacles ≥ 6 mm in height were recorded to be consistent with ASTM F 1637 (ASTM, 2013), which is an accepted international safety standard specifying that abrupt changes in walkway elevation less than 6 mm do not require remediation (implying an acceptably low potential to cause a trip).

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 applicability to natural gait without a recognized threat of a trip, which was the focus of this study.

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 (Fig. 2). Before gait testing began, subjects stood in the middle of the walkway, near where MTC was subsequently measured, 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. Ten gait trials were then 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 (Fig. 2). 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. Only one swing phase from each foot was analyzed from each trial because our walkway was not perfectly level (variations on the order of 1 cm over the entire 10 m), and we only wanted to determine MTC near the "toe-tap" that we used to define floor level. Virtual markers along the bottom of the anterior edge of the shoe (Fig. 2) were defined within a shoe-fixed coordinate system (Startzell and Cavanagh, 1999). All data processing and computations for calculating POT (described below) were performed using custom-written software in Matlab (Mathworks, Inc., Natick, MA).

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 (Fig. 3). Prior work has also used multiple locations on the shoe/sole to determine MTC (Thies et al., 2011).

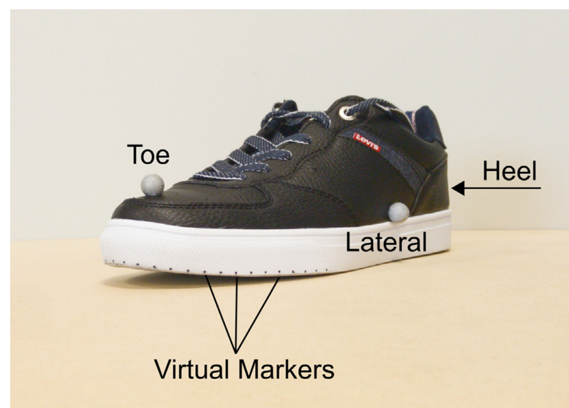

Fig. 2. Photograph of the shoes worn by subjects showing the placement of physical markers and virtual markers. The positions of the virtual markers were defined within a shoe-fixed coordinate system based upon the three physical markers shown.

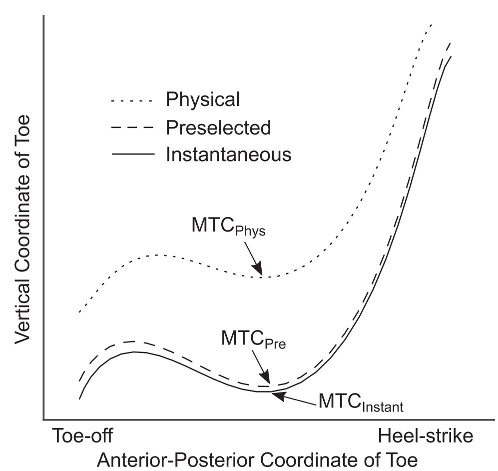

Fig. 3. Sample comparison of the three methods of determining toe trajectory during swing, and the corresponding minimum toe clearance (MTC) for each. MTC_{Phys} and MTC_{Pre} are the trajectories of an individual physical marker and virtual marker on the shoe as described in the text. $MTC_{Instant}$ is the resulting trajectory when using, from each from of the marker data, the coordinate of the most anterior virtual marker.

Unlike this prior study, our method only considered locations on, and therefore obstacles impacting, the "leading edge" of the shoe. We did not consider a trip to have occurred when an obstacle would have contacted the bottom sole of the shoe. While contact with the bottom of the sole can interrupt foot motion and result in a trip, we elected to not consider them due to greater difficulty in predicting the extent to which swing foot motion would be altered by the largely tangential contact between an obstacle and the bottom surface of the shoe.

POT was determined for each swing phase using the toe trajectory of the instantaneous anterior-most virtual marker. We chose to use this trajectory, rather than the other two trajectories, because it was felt that it most closely matched how trips actually occur (an obstacle impacting the instantaneous anterior-most point on the shoe). 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 2695 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 40 mm "threshold" and above the toe trajectory, normalized by the length (i.e. distance) of swing (Fig. 4). 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.

3. 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 (Fig. 5). 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 (Fig. 6), 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 $\pm$ 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 a SEE of 0.029%, which was 37% lower than $MTC_{Instant}$, and the lowest of all alternative measures that exhibited reasonably uniform residuals (Fig. 7 and Supplementary material).

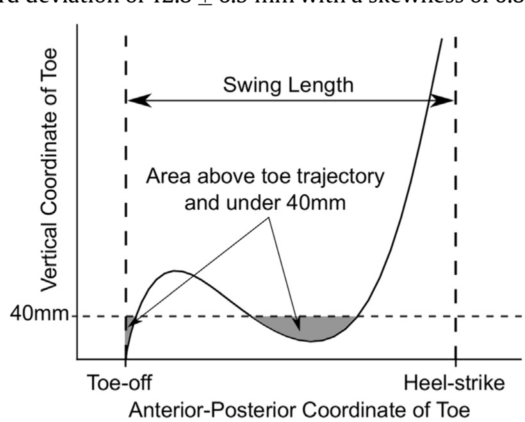

Fig. 4. Schematic illustrating the calculation of the alternative measures that best predicted the probability of tripping. The alternative measure was calculated as the area below 40 mm and above the toe trajectory, divided by swing length, and is abbreviated as MD40.

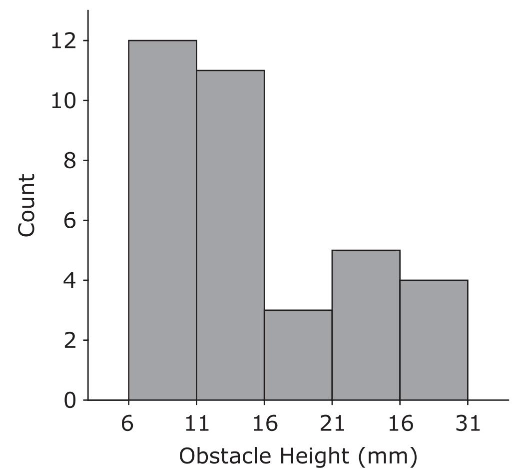

Fig. 5. Distribution of tripping obstacles (abrupt changes in elevation) measured along 2695 steps (i.e. 2.1 km) of heavily-used, paved sidewalks on a university campus. Obstacles with heights less than 6 mm were not included.

4. 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 (Fig. 6), 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% POT 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

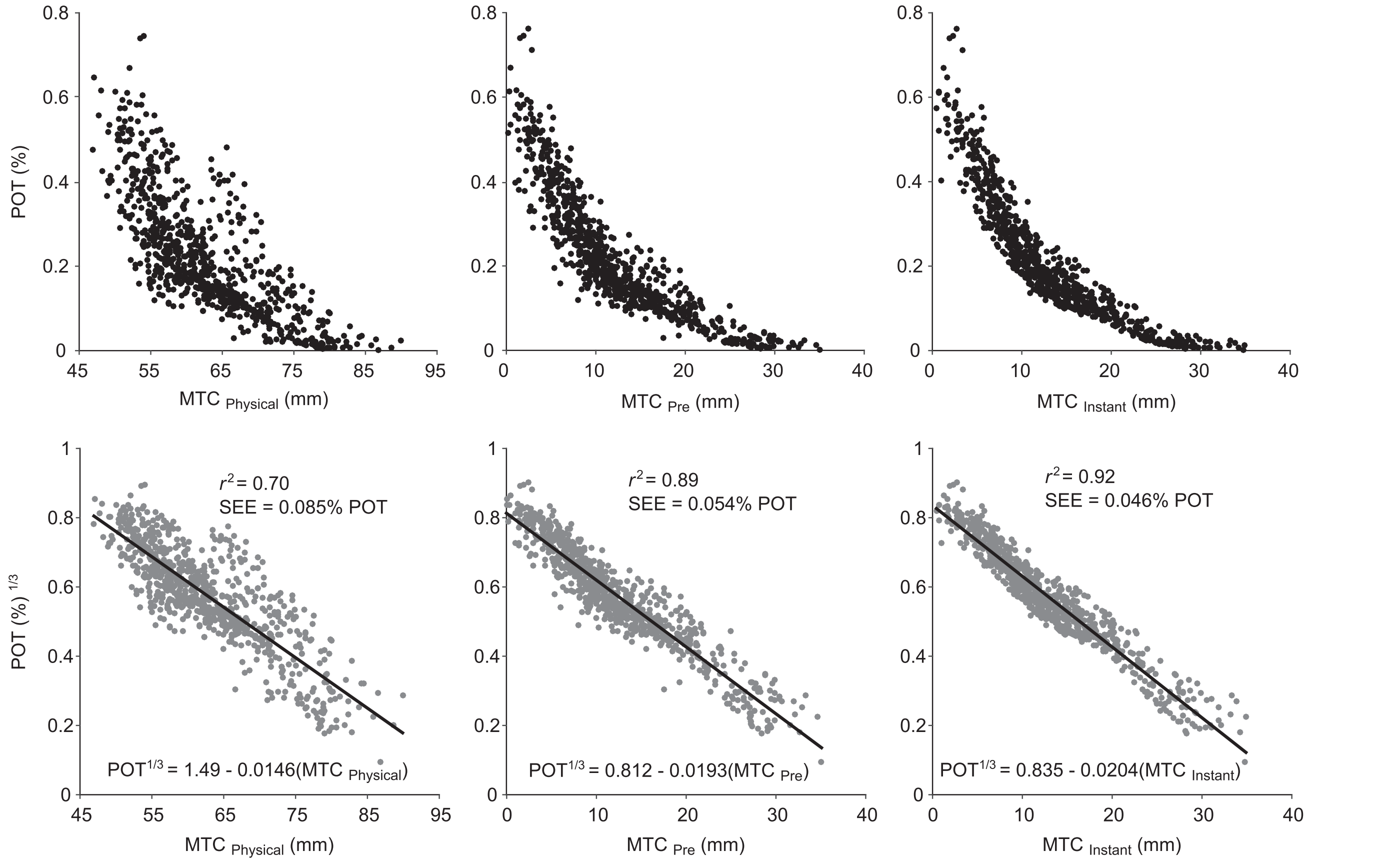

Fig. 6. Scatterplots illustrating a curvilinear relationship between minimum toe clearance (MTC) and the probability of tripping (POT) (upper row), and regression lines used to predict the cube root of POT from MTC (lower row). When using these regression equations, MTC should be in units of mm, and 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.

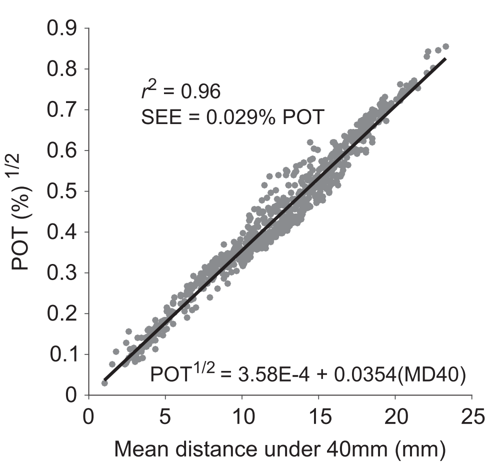

Fig. 7. Scatterplot illustrating the relationship between MD40 (area below 40 mm and above toe trajectory, divided by swing length) and the probability of tripping (POT), including a regression line with necessary transform to achieve a linear relationship and lowest standard error of the estimate.

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 30 mm 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=0.076%; 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 gait when tripping obstacles are unexpected and unseen. 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 anterior-posterior trajectory of the swing foot, and assume any obstacle would exist within this plane. Fourth, POT values, and the regression models that predict POT from MTC, are specific to the distribution of obstacle heights used to estimate POT. Fifth, 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. Sixth, 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 of 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 single swing phase, *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 $MTC_{Instant}$ 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 2695 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 $MTC_{Instant} = 1.2$ 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 2695 steps that involved a tripping obstacle greater than 1.2 cm (13 steps out of 2695 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. Ultimately, a higher level of predictive validity for the methods developed here will require investigating the association between POT/MD40 and the frequency of tripping during everyday life.

5. Conclusion

This study called into question the implicitly-assumed association between MTC and POT held in prior research. A method was developed to calculate POT during gait, and was used to determine the direct, quantitative relationship between MTC and POT. More accurate ways to predict POT from toe trajectory were also investigated. 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.

Conflict of interest

The authors have no conflicts of interest to report.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jbiomech.2016.10.045.

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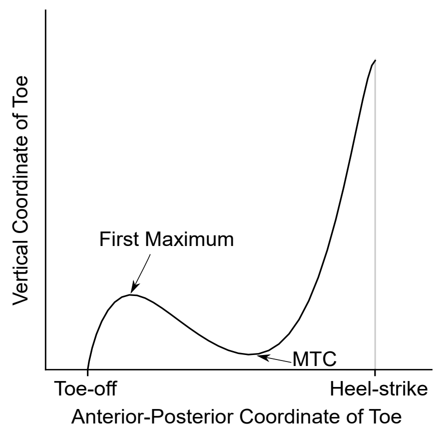
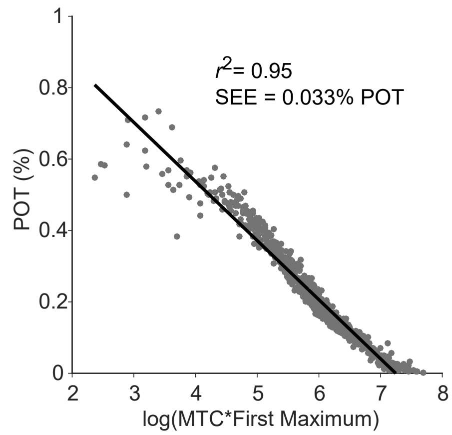
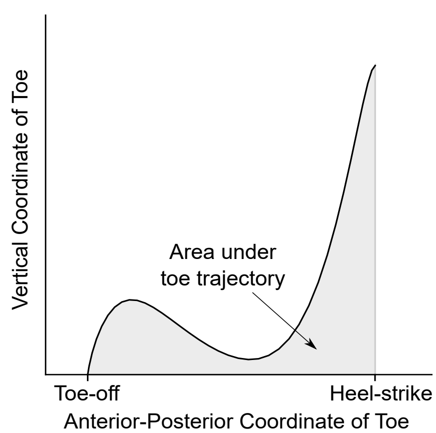
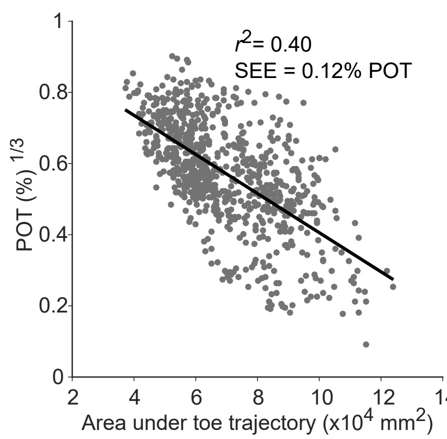
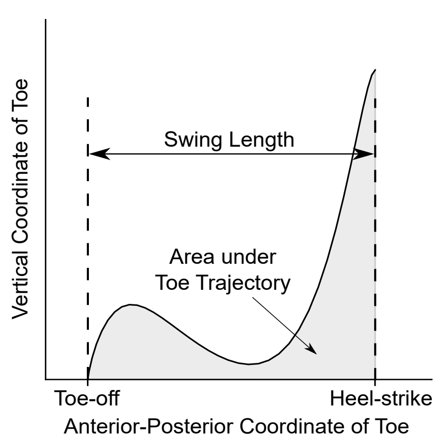
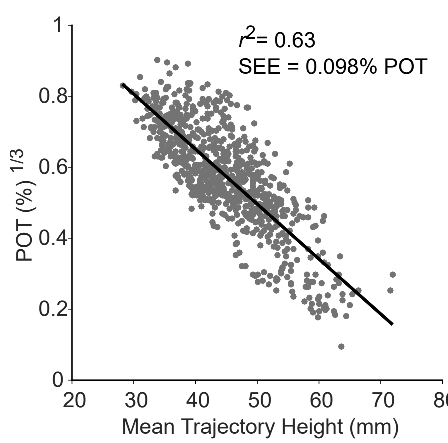
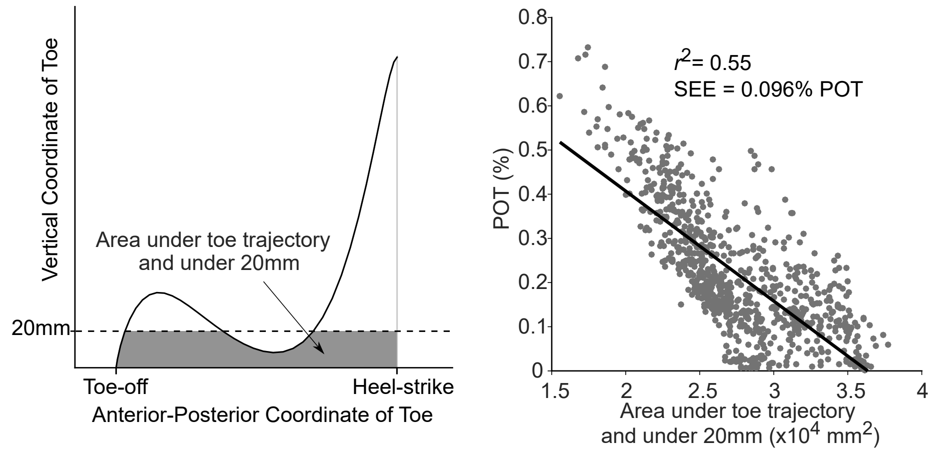
Supplementary material for

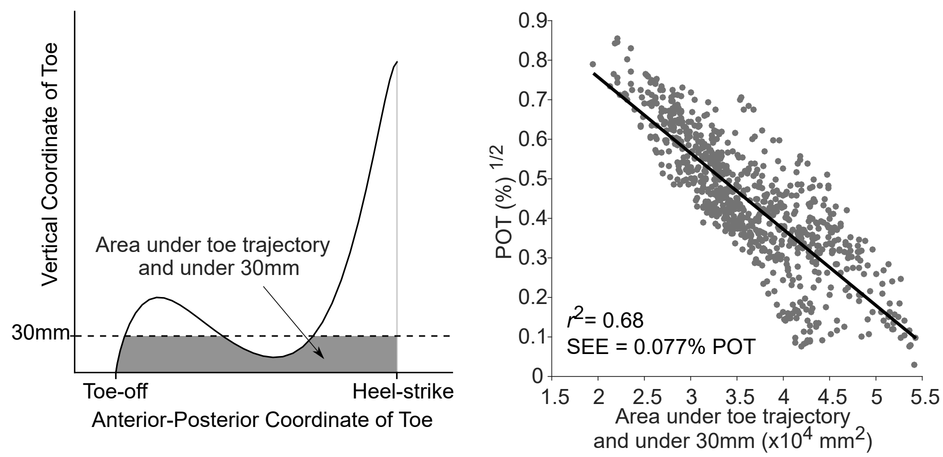
Alternative measures of toe trajectory more accurately predict the probability of tripping than minimum toe clearance

Measure of Toe Trajectory	Graphical description of measure of toe trajectory	Scatterplot of measure of toe trajectory and POT
log(Minimum Toe Clearance * First Maximum)		
Area under toe trajectory		
Mean Trajectory Height = (Area under Toe Trajectory)/ (Swing Length)		

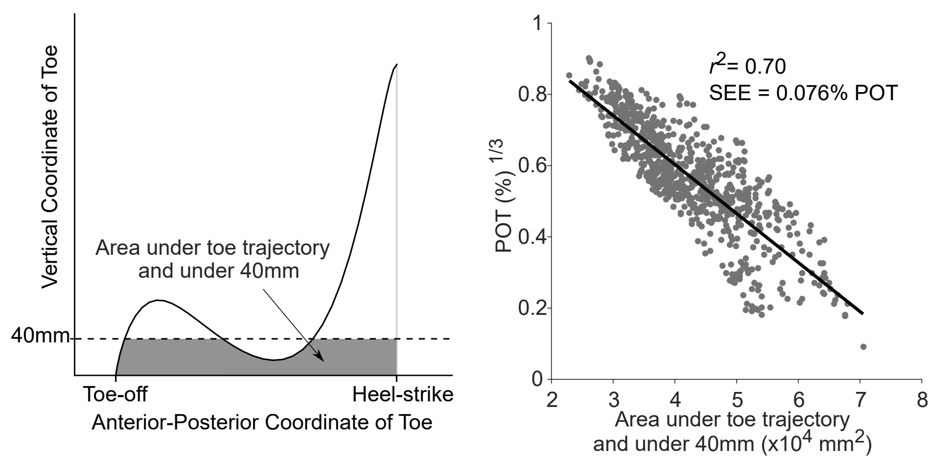
Area under toe trajectory and under 20mm



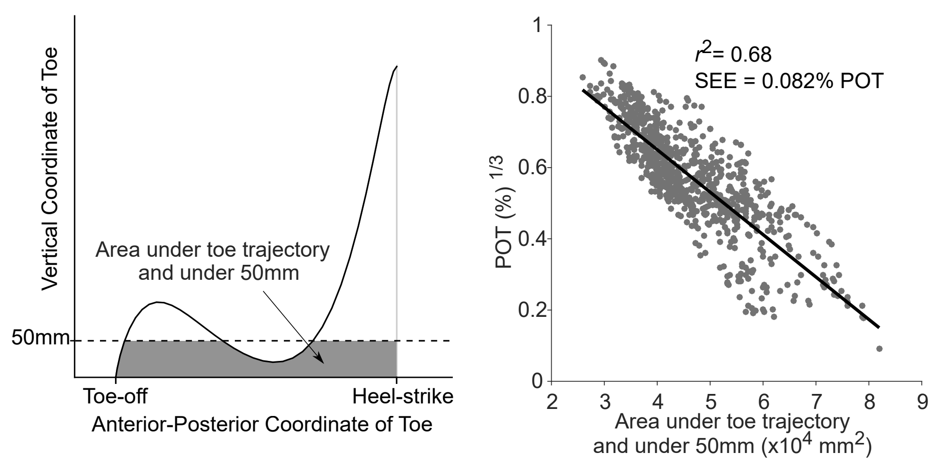
Area under toe trajectory and under 30mm



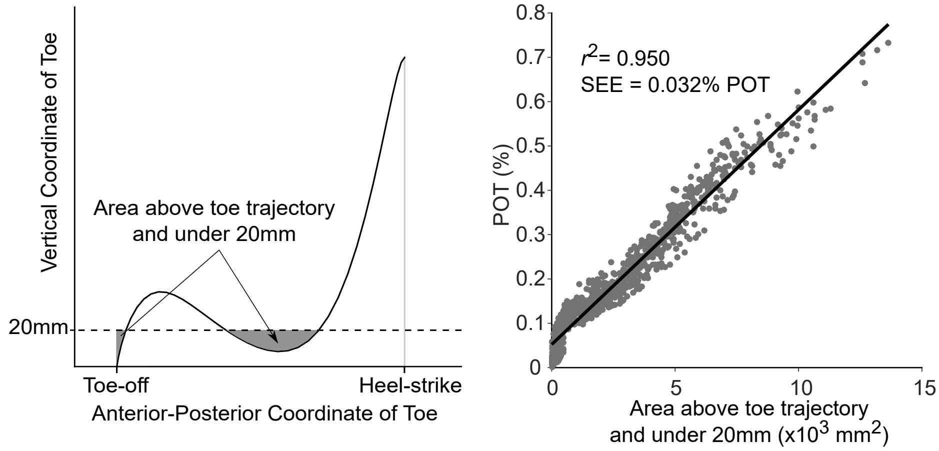
Area under toe trajectory and under 40mm



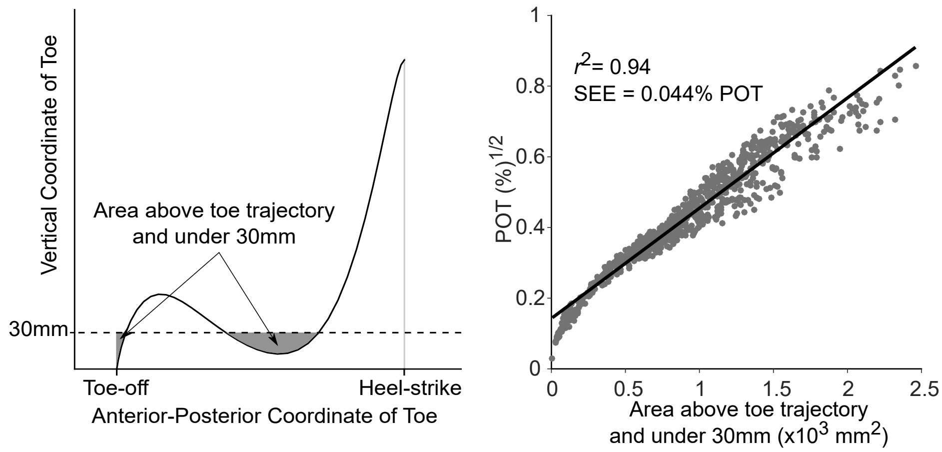
Area under toe trajectory and under 50mm



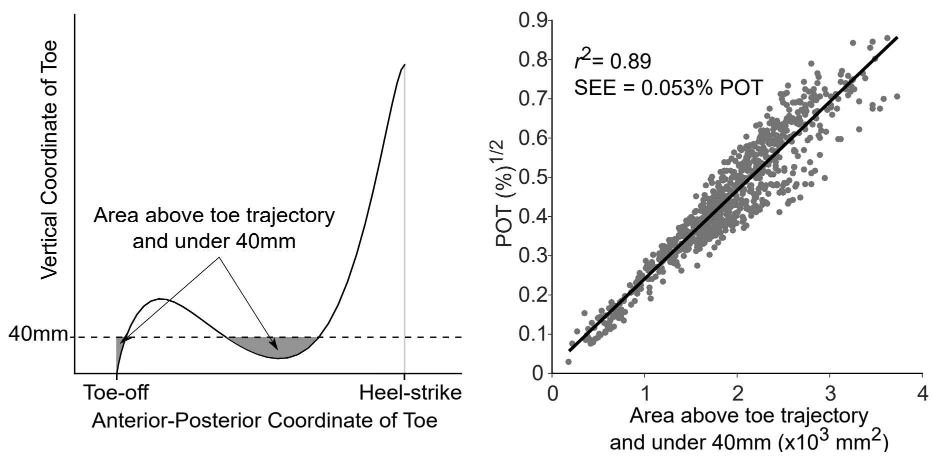
Area above toe trajectory and under 20mm



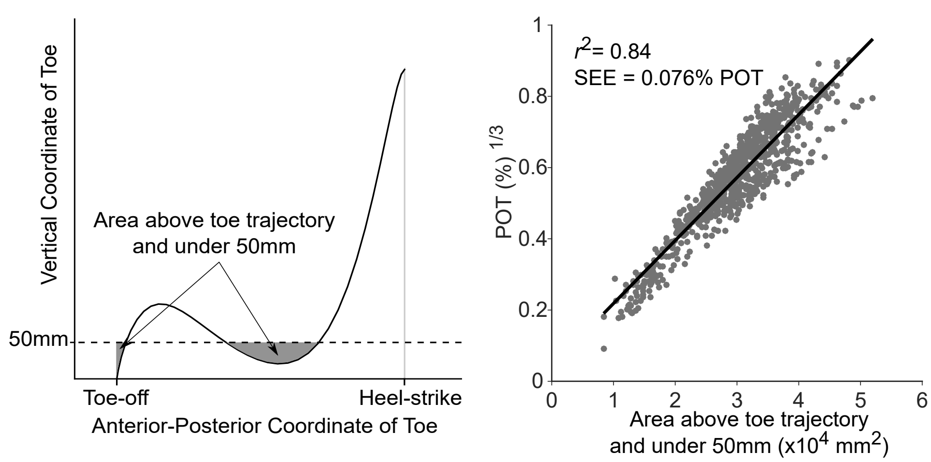
Area above toe trajectory and under 30mm



Area above toe trajectory and under 40mm



Area above toe trajectory and under 50mm



Mean distance under 20mm = (Area above toe trajectory and under 20mm)/(Swing Length)

Mean distance under 30mm = (Area above toe trajectory and under 30mm)/(Swing Length)

Mean distance under 50mm = (Area above toe trajectory and under 50mm)/(Swing Length)

Radius of Curvature at MTC