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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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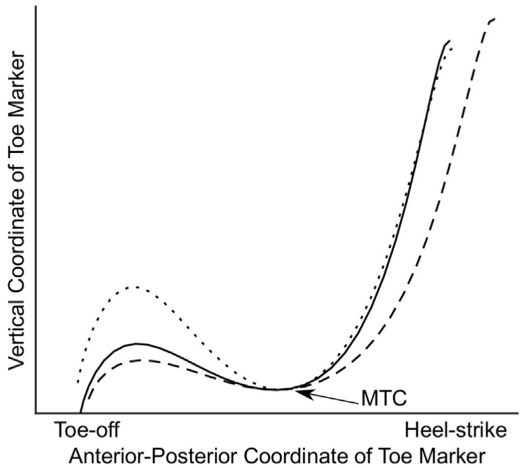

Fig. 1. Three sample toe trajectories during the swing phase of gait, illustrating variability between swing trajectories during phases other than the point of MTC. Intuitively, these three trajectories should be associated with different probabilities of tripping, since a tripping obstacle with a height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

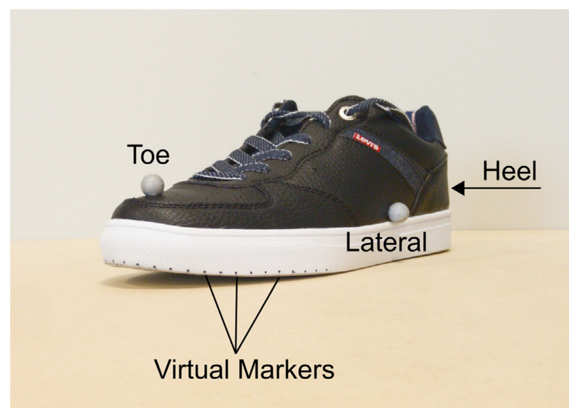

Fig. 2. Photograph of the shoes worn by subjects showing the placement of physical markers and virtual markers. The positions of the virtual markers were defined within a shoe-fixed coordinate system based upon the three physical markers shown.

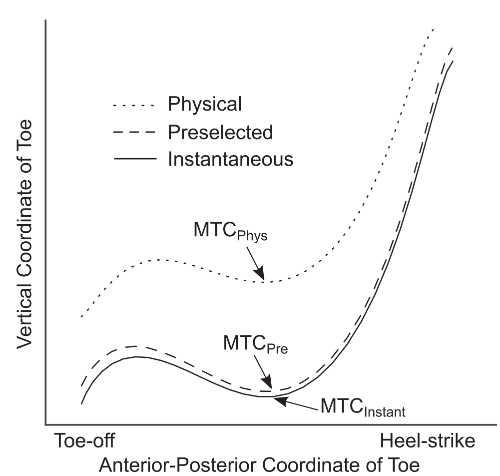

Fig. 3. Sample comparison of the three methods of determining toe trajectory during swing, and the corresponding minimum toe clearance (MTC) for each. MTC_{Phys} and MTC_{Pre} are the trajectories of an individual physical marker and virtual marker on the shoe as described in the text. $MTC_{Instant}$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