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A new measure of trip risk integrating minimum foot clearance and dynamic stability across the swing phase of gait

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Abstract

Minimum toe clearance (MTC) is thought to quantify the risk of the toe contacting the ground during the swing phase of gait and initiating a trip, but there are methodological issues with this measure and the risk of trip-related falls has been shown to also be associated with gait speed and dynamic stability. This paper proposes and evaluates a new measure, trip risk integral (TRI), that circumvents many issues with MTC as typically calculated at a single point by considering minimum foot clearance across the entire swing phase and taking into account dynamic stability to estimate risk of falling due to a trip rather than risk of the foot contacting the floor. Shoes and floor surfaces were digitized and MTC and TRI calculated for unimpaired younger ($N=14$, age= 26 ± 5), unimpaired older ($N=14$, age= 73 ± 7), and older adults who had recently fallen ($N=11$, age= 72 ± 5) walking on surfaces with no obstacles, visible obstacles, and hidden obstacles at slow, preferred, and fast gait speeds. MTC and TRI had significant ($F=5$, $p=0.005$) but differing effects of gait speed and floor surface. As gait speed increased (which increases risk of trip-related falls) MTC indicated less and TRI greater risk, indicating that TRI better quantifies risk of falling due to a trip. While MTC and TRI did not differ by subject group, strong speed-related effects of TRI ($F=8$, $p=0.0007$) resulted in improved TRI for fallers due to their slower self-selected preferred gait. This demonstrates that slower gait is both an important covariate and potential intervention for trip-related falls.

Keywords

minimum toe clearance; irregular floor; obstacles; tripping; older adults; fallers; dynamic stability

1. Introduction

Minimum toe clearance (MTC), or more generally minimum foot clearance (MFC) when the heel is also considered, is thought to be a measure of the risk of the swing foot contacting the walking surface or other object during the swing phase of gait and initiating a trip and fall (Winter, 1992). Recent work has demonstrated that stumbles were more frequent in transtibial prosthetic users with lower prosthetic-side MTC (Rosenblatt et al., 2016) and an intervention in patients with stroke and multiple sclerosis caused a concomitant increase in

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MTC and reduction in falls (Gervasoni et al., 2016), but MTC or MFC have not yet been shown to prospectively predict falling. This may in part be due to multiple methodological issues with the definition and calculation of MTC, the first of which is that MTC is frequently assumed to occur at a single point. When this assumption has been tested it has shown to be invalid, with a single point underestimating MTC (Thies et al., 2011), the true point of MFC occurring at different points on the shoe for different locomotor tasks (Loverro et al., 2013), and even changing location with gait speed and when walking on different surfaces (Schulz et al., 2013). Furthermore, a stereotypical MTC occurring at a local minima occasionally does not exist, especially on uneven or irregular surfaces, or a single swing phase could have multiple local minima, particularly on uneven surfaces (Schulz, 2011; Santhiranayagam et al., 2016; illustrated on Fig. 1a & b). In the latter case should the global minimum be used or does the existence of more than one local minima itself increase trip risk? Even the assumption that the MTC point near the middle of the swing phase poses the greatest risk may not be valid for all shoe types, surfaces, and locomotor tasks, as the heel can have its own even lower local minimum later in the gait cycle (Loverro et al., 2013) where shoes with heels could catch on obstacles on the floor (Fig. 1c). Another issue with MTC is that it is affected by gait speed (De Asha & Buckley, 2015; Schulz, 2011; Schulz et al., 2013) and that differing gait speeds between subject cohorts or related to methods of testing (i.e. treadmill vs. overground) could cause apparent group effects that are actually due only to differences in gait speeds.

While the concept that the proximity of the foot to the ground at midswing increases trip risk is sound, the quantification of this risk would be improved by a more comprehensive measure that 1) takes into account the clearance between the entire foot and walking surface rather than just the toe, 2) considers the entire swing phase rather than a single point, and 3) takes into account the dynamic stability of the subject during the swing phase to quantify the instability of the locomotor system should the swing foot make contact with the ground. Such a measure would facilitate the comparison of trip risk across different surfaces and gait speeds where the MTC as defined by a single spatial point at a single instant during the swing phase is difficult to apply or might generate misleading results. This paper proposes a new measure that incorporates both dynamic stability and MFC throughout swing phase, then contrasts this new measure to a more conventionally calculated MTC in three disparate subject cohorts walking at a range of gait speeds on three different surface conditions.

2. Methods

2.1. Subjects and instrumentation

Data from the unimpaired younger subjects (defined by age range of 18–35) reported in Schulz, 2011 (N=14; half female; ages 20–35; mean±standard deviation 27±5 years) are included here along with two additional subject cohorts of older subjects- unimpaired/non-fallers (N=14; half female, ages 66–82; 72±5 years) and fallers (N=11, 2 female, ages 70–89; 75±6 years). The inclusion criteria for both unimpaired subject cohorts (younger and older) were no major health problems, good balance as defined by one-legged stance times of over 30 seconds on each foot, and to have not fallen in the past six months. Both older subject cohorts (non-fallers and fallers) were defined as age ≥65 years and fallers must have

experienced a fall to the ground in the last six months but could walk without an assistive device. Informed consent was obtained from all subjects in writing and the experimental protocol was approved by the University of South Florida Institutional Review Board. The shoes and floor were instrumented and digitized as described in (Schulz, 2011). Complete details are included in this reference and in the supplementary material, but in summary the soles of a set of experimental shoes were digitized and located relative to retroreflective markers embedded in the shoe soles. Three different flooring surfaces (1- flat, smooth, level floor; 2- multiple small visible obstacles; 3- identical obstacles but hidden from view) were also digitized and located relative to the global laboratory coordinate system. Subjects were instrumented with the Plug-In-Gait upper body marker set and a cluster-based lower-body marker set that located knee and ankle joint centers relative to the shank clusters (Schulz and Kimmel, 2010). A 13-camera Vicon MX40 motion capture system was used to collect marker position data at 120Hz using Workstation v5.2.9 (Vicon, Centennial, CO).

2.2. Data collection

Each subject performed four gait passes for each combination of three speeds and three flooring surfaces for a total of nine conditions and 36 trials. The three instructed speeds were “slower than preferred”, “preferred”, and “as fast as safely possible” and the three flooring surfaces were “no obstacles”-flat, smooth, level surface, “visible obstacles”-white obstacles on black surface, and “hidden obstacles”-black obstacles on black surface. Surface conditions were presented in randomized order and speed conditions were randomized within each surface condition. Instructed speed conditions were not tightly controlled to permit changes in actual speed across flooring surfaces due to perceived challenge. If a faller exhibited any indications of fatigue during an earlier day of clinical testing not reported here (i.e. needing additional rest time during or between any of the clinical assessments), then the slow speed trials were not collected for that subject. Five of the eleven older fallers deviated from the protocol used by the unimpaired subjects by not performing slow speed trials. A safety harness was worn at all times to minimize the chance of fall-related injuries.

All trials were conducted under identical low lighting conditions designed to minimize visual feedback of obstacle location for the hidden obstacles surface condition while retaining visibility of the rest of the laboratory, subject, and visible obstacles. Subjects were not allowed to see the hidden obstacles surface under normal lighting conditions and were instructed that the obstacles on this surface were identical to the visible obstacles in size, shape, and number, but that their layout was only “similar” while in fact their layout was identical. Subjects were not allowed additional time to adapt to the low lighting and were initially not given specific instructions regarding gaze fixation. No obvious or extreme differences in head orientation and position between flooring surface conditions were observed for all of the young subjects and several of the unimpaired older subjects until one of the unimpaired older female subjects attempted to circumvent the masking of the hidden obstacles via substantial waist, trunk, and neck flexion intended to get her head much closer to the floor and thus improve her ability to see the hidden obstacles. The additional time required for older adults to adapt to low lighting (Tahir et al., 2016) may have played a role in this unforeseen behavior, but to compensate for it an additional instruction to keep their eyes focused on the end of the walkway for the hidden obstacles condition was given to this

subject and all subsequent subjects to ensure that the hidden obstacles would be obscured and to prevent the substantial kinematic changes that would otherwise have occurred. No significant differences were found in performance of unimpaired older subjects before and after these additional instructions, but given the smaller sample size of these comparisons (within one group on a single surface) this does not conclusively demonstrate that this additional instruction did not affect performance in any way. However, this does indicate that any effects, if present, would likely be small and unlikely to alter the findings presented here.

2.3. Data processing

Marker data were labeled using Vicon Workstation, then processed using Visual3D (C-Motion, Inc., Germantown, MD) and custom MATLAB code (MathWorks, Natick, MA) as described in (Schulz, 2011) and detailed in the supplementary information. In summary, the minimum toe and heel clearances were calculated as the time series of the minimum distance between all digitized points on the toe and heel shoe segments and the interpolated floor surface beneath each point for every frame of data. For surfaces with obstacles, the minimum resultant distance between peak of any obstacle and shoe was also calculated and the lesser value (vertical distance from shoe to floor or resultant distance from shoe to any obstacle) used to define the minimum toe and heel clearances. Lower limb joint centers were determined functionally (Schwartz and Rozumalski, 2005) and whole-body Center-of-Mass (CoM) location calculated using DeLeva's adjustments to Zatsiorsky-Seluyanov segmental mass locations and distributions (de Leva, 1996). Gait speed was normalized to leg length.

As previously reported (Schulz, 2011), MTC events where a fall would be likely to occur if the swing foot were to contact an obstacle as described by Winter (Winter, 1992) were operationally defined to occur when: 1) The minimum distance between the toe and ground was at a local minimum (value was less than that for preceding or following two frames), 2) Toe segment speed (mean of the four toe markers) was within the upper quartile for that swing phase, and 3) The minimum clearance to the heel segment was not smaller than the minimum clearance to the toe segment. The second condition was used to eliminate erroneous MTC events from occurring immediately after foot off. The third condition was added to prevent erroneous MTC events from being detected at midfoot where the posterior edge of the toe segment is adjacent to the anterior edge of the heel segment. This situation would occur if the location of the point of minimum clearance between shoe and ground moved from the toe segment to the heel segment without experiencing a local minima while on the toe segment (e.g. second MTC minimum in Fig. 1c). Note that these MTC values are the minimum (by gait cycle) of the minimum (by all of the digitized points on the toe segment) toe clearance. If these criteria were met by more than one point per gait cycle (more common on surfaces with obstacles, e.g. Fig. 1b), then the point with the smaller MTC value was used.

2.4. Definition of new measure of trip risk

The new measure was calculated based on the assumptions that 1) Lower MFC increases the risk of the foot contacting the ground or other obstacle and disrupting gait or stepping and 2)

Less dynamic stability would increase the severity of the disruption to the gait cycle if the foot were to contact the ground or other obstacle.

MFC for the entire shoe was used rather than MTC to account for the clearance of the entire foot. The dynamic stability measure used here was calculated based on the margin of stability (MoS, Hof et al., 2005) in the direction of progression:

$$MoS = u_{\max} - xCoM, \text{ where } xCoM = x + \frac{v}{\sqrt{g/l}} \quad (1)$$

Where MoS is the margin of stability; $u_{\max}$ is the boundary of the base of support; $xCoM$ is the location of the extrapolated center of mass; x is the position and v is the velocity of the CoM; g is the gravitational constant and l is the effective pendulum length. While MoS is a continuous trajectory, it is reported as the single minimum value per gait cycle during double support (i.e. it is not calculated during the swing phase) and is stable when positive and unstable when negative (i.e. additional actions must be executed to maintain balance). Since a measure of the degree of instability throughout swing phase was required here, three modifications were made to the MoS: 1) the continuous MoS trajectory during swing phase was used and the most anterior toe tip marker (on either foot) considered to be $u_{\max}$ (i.e. on the stance toe for early swing and on the swing toe during late swing- where the anterior boundary of the base of support would be if the swing foot were to contact the ground), 2) stable (i.e. positive) MoS values were set to zero, 3) MoS was negated to create a measure of instability should the foot contact the ground during the swing phase. This modified version of the MoS will be subsequently referred to here as the Margin of Instability (MoI).

The trip risk trajectory was then calculated by dividing the MoI trajectory (in mm) by the MFC trajectory (also in mm) across the duration of the swing phase of gait, which results in a dimensionless trip risk trajectory (Fig. 2). To quantify the total trip risk across the swing phase, the integral of this measure was taken, but spikes in the trip risk trajectory would often occur at foot liftoff or landing (Fig. 2). To exclude these spikes when the foot was intentionally and necessarily in close proximity to the ground, the integral was taken between the time points of peak MFC acceleration to exclude these erroneous spikes and still capture all values between the initial liftoff acceleration of the foot and the terminal deceleration prior to foot contact (Fig. 2). The resulting trip risk integral (TRI) is thus calculated as per equation 2:

$$TRI = \int_{FO_{acc}}^{IC_{acc}} \frac{MoI}{MFC} dt \quad (2)$$

Note that time was not normalized and integration step size was dictated by the motion capture data collection rate of 120Hz to be 0.0083s. This means that, if MoI and MFC did not vary with speed, slower gait speeds with swing phases of longer duration would be expected to have greater TRI values.

2.5. Statistical analysis

A repeated-measures linear mixed model was used to test the effects of the three independent variables of subject group, flooring surface, and actual gait speed on two dependent variables (MTC and TRI) using SAS (SAS Institute Inc., Carey, NC). All interaction effects were also included in the model. Mixed models account for missing data well as long as the data are missing at random, but incomplete data were collected for the fallers. Therefore, this randomness assumption was tested using Little's Missing Completely at Random test in SPSS (IBM Corporation, Armonk, NY) and found to be valid. Although gait speed was controlled by categorical instructions of "slow", "preferred", or "fast"; the resulting actual gait speed in leg lengths per second was tested as a continuous variable to evaluate the differences in MTC and TRI at preferred speed and the effects of actual gait speed rather than subject responses to instructions or capabilities. Uncorrected p-values were reported but threshold of significance was corrected as per Bonferroni- main effects considered significant at $p < 0.008$ ($0.05 / (3 \text{ independent variables} \times 2 \text{ dependent variables})$). If main effects for group or surface were significant, post-hoc multiple comparisons were conducted.

3. Results

Testing was well tolerated by all subjects and only one older male non-faller stumbled due to contact with an obstacle (fast gait speed on visible obstacles surface). He recovered within one or two steps and the obstacle contact and recovery steps were excluded from analysis. No subjects fell into the harness.

All subjects walked faster when instructed ($F=580$, $p < 0.0001$) and slower on surfaces with obstacles ($F=8.3$, $p=0.0006$, Fig. 3). Fallers walked slower at all instructed speeds ($F=14$, $p < 0.0001$) such that the actual gait speeds of the fallers at preferred and fast instructed gait speeds were closer, respectively, to the actual gait speeds of the unimpaired younger and older subjects at slow and preferred instructed gait speeds (Fig. 3). Foot placement data reported elsewhere indicated that subjects actively avoided visible obstacles, but foot placement on no obstacles and hidden obstacles surfaces were similar, indicating that hidden obstacles were indeed not visible as intended (Schulz, 2012).

MTC and TRI were both greater for faster gait speeds (Fig. 4; $F=61$ and 311 respectively; both $p < 0.0001$), but these are opposite effects in that greater MTC values indicate less risk (foot farther from floor) while greater TRI values indicate greater risk. MTC was greater on surfaces with obstacles ($F=24$, $p < 0.0001$) while TRI was smaller ($F=8.1$, $p=0.0007$), but TRI exhibited a strong floor*speed interaction effect ($F=74$, $p < 0.0001$). This interaction effect was present but much weaker for MTC ($F=5.5$, $p=0.005$). Linear regressions for MTC and TRI on actual gait speed were calculated on each surface to better visualize and quantify these interactions (Fig. 4). The slope of these regressions show that the increase in TRI with speed on surfaces with obstacles was roughly half that of the increase on the no obstacles surface (52% for visible obstacles and 41% for hidden obstacles, Fig. 4).

Neither MTC nor TRI exhibited any main effect of subject group, although the significantly slower self-selected gait speeds of the older fallers (Figs. 3 & 4) would make a group effect

appear to exist for TRI if gait speed was not adequately controlled for ($F=10$, $p=0.0005$ if instructed rather than actual gait speed included in model). The significantly slower self-selected gait speeds of the fallers resulted in reduced TRI at equivalent instructed speeds, but not for equivalent actual speeds (Fig. 4).

TRI did also have a significant group*speed interaction ($F=5.5$, $p=0.005$), but this was likely due to the floor effect of TRI at very slow gait speeds. As per equation 1, MoS is stable and positive when $u_{\max} > x\text{CoM}$ which results in a MoI and TRI of zero when this condition is met. In practice, this occurred for gait slower than ~ 1 leg length/s or $\sim 0.75\text{m/s}$. As the self-selected slow speed of the fallers was frequently slow enough to encounter this floor effect while the slow speeds of the two unimpaired groups were not, a group*speed effect was detected.

4. Discussion

According to both MTC and TRI, all three subject cohorts adapted similarly to different flooring surfaces and speeds. Both MTC and TRI indicate that adaptations to flooring surfaces would reduce the risk of tripping in all three subject cohorts tested, but the main effect of flooring surface was dominant for MTC while the flooring*speed interaction was dominant for TRI (Fig. 4). However, as gait speed increased MTC improved (toe further from floor indicating less risk) while TRI worsened (indicating more risk). This apparent contradiction can be explained by the differing constructs measured by MTC and TRI. MTC quantifies the risk of the toe contacting the floor and potentially initiating a trip; while TRI, because it incorporates a measure of dynamic stability, is intended to quantify the risk of falling due to a trip. This positive correlation of gait speed and the risk of falling due to a trip as estimated by TRI is supported by the earlier work of Pavol and colleagues, who demonstrated that increased walking speed may be the greatest cause of falling following a trip in older adults (Pavol et al., 2001). Conceptually, this is also supported in the opposite direction by the example of a very slow and impaired patient with a shuffling gait where neither foot ever leaves the ground who nonetheless can ambulate without falling. In this case $\text{MTC}=0$ because both feet are always in contact with the ground, but the patient does not fall because the gait speed is so slow that the MoI never leaves the region of stability and consequently TRI is also zero.

The strong positive relationship between TRI and gait speed (note that this is the opposite of what would be expected based on the shorter integral durations of faster steps) could lead to apparent differences between subjects or subject groups that are entirely due to differences in gait speed. This complicates the interpretation of these effects and accentuates the importance of adequately controlling for gait speed differences, since TRI indicates that subjects who choose to (or are only able to) walk at slower speeds would have a reduced risk of falling due to a trip.

The primary limitation of TRI is that its calculation requires more data than a simple measure of MTC using a single real or virtual marker on the toe. The walking surface and shoes must be digitized and the distance between them accurately calculated to determine MFC and the CoM position and velocity must also be obtained to calculate MoI. While this

requires greater effort, time, and equipment; there are several potential methods to minimize the cost and effort to collect these additional data. For example, the shoe data reported here were collected by instrumenting and digitizing a set of laboratory shoes using a manual pointer, a time-consuming procedure, but the current availability and relative affordability of 3D scanners and processing systems would make obtaining a high-quality scan of a subject's own shoes while they are being worn possible in a reasonable amount of time. Similar scanning systems, such as the Microsoft Kinect (Microsoft Inc., Redmond, WA) or Google Tango (Google, Mountain View, CA), could be used to map the laboratory flooring instead of the custom rolling wand used to map the floor for the data presented here. To calculate the CoM a full-body marker set was used here, but a single marker located near the CoM has been shown to be an adequate representation of the actual CoM position for gait (Yang and Pai, 2014).

It should be noted that TRI was named for what it intends to quantify and has not yet been validated to predict the risk of tripping or falling. However, a recent study by Byju and colleagues (Byju et al., 2016) found that a measure of toe clearance across the entire swing phase – the area above the toe trajectory but below 40mm – predicted the probability of tripping better than MTC. While this measure did not consider the entire foot nor incorporate dynamic stability, these findings indicate that foot clearance across the duration of swing phase as incorporated in TRI is similarly likely to predict the probability of tripping better than conventional instantaneous measures of foot clearance. Additionally, TRI as initially presented here is a purely sagittal plane measure that does not take into account non-anterior movement or instability in the transverse or frontal planes. Future variants of this measure could be expanded to consider dynamic stability in these other planes as well as movement in other directions or more complicated tasks. Furthermore, the type of shoe was controlled here, but the effects of shoe type on TRI warrant further investigation, as different heel height, toe spring, rocker profile, or other shoe characteristics could alter TRI.

In summary, the proposed trip risk integral (TRI) successfully captures dynamic gait stability and minimum foot clearance across the entire swing phase of gait in a single measure that circumvents many conceptual and methodologic issues associated with minimum toe clearance and may better quantify the risk of falling due to a trip. This measure also highlights the importance of gait speed in the risk of falling due to a trip, both as a potential covariate and as a potential mechanism to reduce the risk of trip-related falls.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Figure 1.

Exemplar data of problematic minimum toe clearance (MTC) and minimum heel clearance data from a single faller subject walking on an uneven surface showing swing phase data a) without a defined MTC, b) with multiple potential MTC points, and c) where the minimum foot clearance occurs at the heel immediately prior to initial contact rather than at the toe near mid swing.

Figure 2.

Exemplar data of swing phase margin of instability (negated margin of stability to tip of swing toe, top left), minimum foot clearance (MFC, bottom left), resultant velocity and acceleration of the point of MFC on the shoe (bottom right), and trip risk (top right) with trip risk integral (TRI) shaded. Time interval for integral established by peak acceleration and deceleration of point of MFC as shown by vertical dashed lines. Subject and shoe position and orientation at points of interest indicated at bottom left and top right.

Figure 3.

Normalized actual gait speed plotted against instructed gait speed by subject group and floor surface. All subjects walked faster when instructed ($F=580$, $p<0.0001$) and slower on surfaces with obstacles ($F=8.3$, $p=0.0006$). Fallers walked slower at all instructed speeds ($F=14$, $p<0.0001$).

Figure 4.

Minimum toe clearance (MTC) data (top row) and trip risk integral (TRI) data (bottom row) for younger non-fallers, older non-fallers, and older fallers while walking at three self-selected speeds (slower than preferred, preferred, and as fast as safely possible) on three surfaces: no obstacles (left column), visible obstacles (middle column), and hidden obstacles (right column). Mean ± 1 standard deviation of TRI values at mean preferred gait speed for each group indicated by large symbols with error bars to illustrate apparent TRI group effect due to slower self-selected gait speeds of fallers. MTC and TRI both increased with speed ($F=61$ and 311 respectively; both $p<0.0001$). MTC was greater on surfaces with obstacles ($F=24$, $p<0.0001$) while TRI was smaller ($F=8$, $p=0.0007$), but TRI exhibited a strong floor*speed interaction effect ($F=74$, $p<0.0001$). This floor*speed interaction effect was present but much weaker for MTC ($F=5.5$, $p=0.005$).