Journal of Biomechanics 48 (2015) 1229–1232

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

A bootstrapping method to assess the influence of age, obesity, gender, and gait speed on probability of tripping as a function of obstacle height

Christina Rossi Garman [a], Christopher T. Franck [a], Maury A. Nussbaum [a], Michael L. Madigan [b],*

[a] Virginia Tech, Blacksburg, VA, USA
[b] Texas A&M University, College Station, TX, USA

ARTICLE INFO

Article history:
Accepted 24 January 2015

Keywords:
Gait
Locomotion
Minimum foot clearance
Tripping
Obesity

ABSTRACT

Tripping is a common mechanism for inducing falls. The purpose of this study was to present a method that determines the probability of tripping over an unseen obstacle while avoiding the ambiguous situation wherein median minimum foot clearance (MFC) and MFC interquartile range concurrently increase or decrease, and determines how the probability of tripping varies with potential obstacle height. The method was used to investigate the effects of age, obesity, gender, and gait speed on the probability of tripping. MFC was measured while 80 participants walked along a 10-m walkway at self-selected and hurried gait speeds. The method was able to characterize the probability of tripping as a function of obstacle height, and identify effects of age, obesity, gender, and gait speed. More specifically, the probability of tripping was higher among older adults, higher among obese adults, higher among females, and higher at the slower self-selected speed. Many of these results were not found, or clear, from the more common approach on characterizing likelihood of tripping based on MFC measures of central tendency and variability.

1. Introduction

Fall-related injuries among older adults are a major public health problem due to their high medical costs and negative impact on quality of life (Bruce et al., 1992). Tripping accounts for 35–53% of these falls (Berg et al., 1997; Blake et al., 1998). The most common measure for characterizing the probability of tripping while walking is the minimum foot clearance (MFC) during swing. A decrease in the central tendency (i.e. mean/median) of MFC, or an increase in MFC variability, are both associated with an increased probability of tripping (Begg et al., 2007; Mills et al., 2008; Winter, 1992). These indirect measures of probability of tripping, however, can lead to ambiguous results when both increase or decrease simultaneously. For example, Nagano et al. (2011) reported higher median MFC and MFC interquartile range (IQR, a measure of MFC variability) during overground walking compared to treadmill walking (Nagano et al., 2011), and Rossi et al. (2013) reported higher median MFC and MFC IQR in the non-dominant leg and at faster gait speeds (Rossi et al., 2013). Median MFC and MFC IQR are also positively correlated (Begg et al., 2007), indicating concurrent increases or decreases in both are to be expected.

The purpose of this study was to present a method that determines the probability of tripping over an unseen obstacle while avoiding the ambiguous situation wherein median MFC and MFC IQR concurrently increase or decrease, and determines how the probability of tripping varies with potential obstacle height. The method was used to investigate the effects of age, obesity, gender, and gait speed on the probability of tripping. These factors were investigated based upon reports of elevated risks of falling and fall-related injuries among adults over the age of 65 (Bruce et al., 1992; Kannus et al., 1999), individuals who are obese (Fjeldstad et al., 2008; Himes and Reynolds, 2012; Patino et al., 2010), females (Ambrose et al., 2013; Stevens, 2005), and changes in risk of tripping with gait speed (Rossi et al., 2013; Schulz, 2011).

2. Methods

Eighty participants completed the study including four gender-balanced groups comprised of 20 participants each (Table 1). None of the participants self-reported a change in body mass of >2.3 kg over the six months prior to testing, or any musculoskeletal, neurological, or balance disorders that would affect gait. The study was approved by the university Institutional Review Board, and all participants provided written informed consent prior to participation.

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* Correspondence to: Department of Biomedical Engineering (3120) 5045 Emerging Technologies Building, College Station, TX 77843-3120, USA. Tel.: +1 979 862 1214.
E-mail address: mlm@tamu.edu (M.L. Madigan).

http://dx.doi.org/10.1016/j.jbiomech.2015.01.031
0021-9290/

Table 1
Participant demographics (mean ± standard deviation).

	Young		Older	
	NW	OB	NW	OB
Sample size	F: ($n=10$) M: ($n=10$)	F: ($n=10$) M: ($n=10$)	F: ($n=10$) M: ($n=10$)	F: ($n=10$) M: ($n=10$)
Age (years)	F: 24.4 ± 3.4 M: 23.8 ± 3.2	F: 24.8 ± 2.8 M: 21.9 ± 2.5	F: 66.8 ± 4.9 M: 65.8 ± 4.6	F: 65.6 ± 5.5 M: 74.3 ± 6.1
BMI (kg/m^2)	F: 23.1 ± 2.2 M: 21.2 ± 1.7	F: 34.0 ± 3.5 M: 33.2 ± 3.1	F: 23.8 ± 2.0 M: 24.5 ± 1.4	F: 33.1 ± 2.0 M: 31.5 ± 1.7

Note: NW = normal-weight group, OB = obese group, F = female, M = male.

Participants walked along a 10-m level walkway at a self-selected speed (always performed first) and a hurried speed of 1.9 m/s. Eight trials at each speed were completed, and data obtained from each trial included the swing phase of both the dominant and non-dominant leg. Thus, 16 swing phases were analyzed from each participant at each speed. The positions of three reflective markers attached to the shoe were sampled at 100 Hz using a Vicon MX motion analysis system (Vicon Motion Systems Inc., LA, CA). Multiple virtual points on the sole of the shoe were tracked using a method described elsewhere (Startzell and Cavanagh, 1999), and MFC was defined as the lowest of all points near mid-swing in a given swing phase.

MFC values were used to create trip probability curves that indicated how the probability of tripping varied as a function of height of a potential tripping obstacle (Fig. 1). For potential tripping obstacle heights ranging from 0–7 cm, in increments of 2 mm, each experimental MFC value was dichotomized as either a trip (if the potential obstacle height was greater than MFC) or a non-trip (if the potential obstacle height was equal to or less than MFC). The percentages of trips at each obstacle height were then computed, serving as an estimate of the probability of tripping.

A statistical bootstrapping technique (Duhamel et al., 2004), was then used at each potential obstacle height to determine whether the probability of tripping differed by age group, obesity group, gender, or gait speed condition. The first step in this technique was to randomly reassign group labels to each of the 16 MFC values from each participant (e.g. young or older when investigating age effects). A probability curve was then created for each group, and the difference in trip probability between groups was calculated at each potential obstacle height. This process was performed 100,000 times to obtain a distribution of differences at each potential obstacle height that would occur if group assignment was random. This distribution acted as the sampling distribution of differences under the null hypothesis that the groups had equal trip probabilities.

The second step in this technique was to determine whether the actual observed difference in probability of tripping between groups was statistically significant. The actual observed difference in probability of tripping between groups was defined as the absolute value of the difference between the group percentages at a potential obstacle height. Because each bootstrapping analysis involved 36 comparisons between groups (0–7 cm obstacles heights in increments of 2 mm), the significance level was 0.05/36, or $\alpha = 0.0014$, to avoid consequences of type I errors. As such, if the actual difference in probability of tripping was in the outer 0.14% of the distribution, then the difference in trip probability between groups was considered statistically significant. Alternatively, the percentage of the distribution of differences outside of the actual observed difference yielded a bootstrap p-value. This second step was performed for all potential obstacle heights, and between all participant groups of interest, to determine the specific heights at which the probability of tripping differed between groups.

Group differences identified from this statistical bootstrapping technique were compared with group differences identified using the traditional measures of median MFC and MFC IQR. Group differences in median MFC and MFC IQR were determined using a four-way, mixed-factor analyses of covariance (ANCOVA) with planned contrasts. Independent variables in the ANCOVAs were age, obesity, and gender, and gait speed was the covariate. Analyses were performed using JMP v7 (Cary, North Carolina, USA).

3. Results

Age-related differences in the probability of tripping were not consistent between the bootstrapping technique and the ANCOVA analysis. Among normal-weight adults (Fig. 1a), the probability of tripping was lower among older adults across a range of obstacle heights (2.0–4.6 cm), while no age effects were found for either median MFC or MFC IQR. Among obese adults (Fig. 1b), the probability of tripping was also lower among older adults, but across a smaller range of obstacle heights (1.2–2.4 cm), while again there were no age effects for either median MFC or MFC IQR.

Obesity-related differences in the probability of tripping were also not consistent between the bootstrapping technique and the ANCOVA analysis. Among older adults (Fig. 1c), the probability of tripping was significantly higher among obese adults across a range of obstacle heights (2.4–4.2 cm), while there were no obesity effects on median MFC or MFC IQR. Among young adults (Fig. 1d), there were no significant effects of obesity on the probability of tripping, nor on median MFC or MFC IQR. With respect to gender (Fig. 1e), the probability of tripping was higher among females across a range of obstacle heights (0.8–4.4 cm), while both median MFC and MFC IQR were lower among females. With respect to speed (Fig. 1f), the probability of tripping was lower for the faster hurried speed across a narrow range of obstacle heights (4.2–5 cm), while both median MFC (approached significance) and MFC IQR were higher at the faster hurried speed.

4. Discussion

While prior work has employed median MFC and MFC IQR as indirect measures of likelihood of tripping, the method presented here directly determines the probability of tripping as a function of obstacle height, and uses a statistical bootstrapping technique to compare this probability between groups of interest. This technique identified effects of age and obesity that were not identified from the more traditional approach using ANOVA. This new technique also identified effects of gender and gait speed, and helped clarify ambiguous results from the ANCOVA analysis with respect to probability of tripping (e.g. when both median MFC and MFC IQR were higher among males compared to females).

Three limitations to the method presented here warrant mentioning. First, this method, along with ANOVA using median/mean MFC and MFC IQR, focuses on foot clearance at the instant that MFC occurs, even though a trip could occur at other instances during the swing phase. Second, unlike an ANOVA based upon median/mean MFC and/or MFC IQR, the current method cannot incorporate measures of covariance, or statistically control for the effects of other variables, when evaluating an independent variable of interest. Third, this method, along with most other investigations of MFC, assumes individuals will not see or react to an obstacle in their path. While this may be true for smaller obstacles, this is less likely for larger obstacles.

The method presented here may be helpful in ensuring that safety guidelines are inclusive and protective for diverse populations. For instance, The Americans with Disabilities Act (ADA) stipulates that abrupt changes in height of a walkway greater than 6 mm require edge treatment to account for individuals in wheelchairs and individuals whose foot is impeded during the swing phase of gait (Cohen and Abele, 2007). The results in Fig. 1c indicate that trip probability does not differ between normal-weight and obese older adults unless obstacle height exceed 2.4 cm, suggesting that the 6 mm standard of the ADA is equally protective for both of these populations.

A statistical modeling technique reported by Best and Begg (2008) also characterizes the probability of tripping over a range of obstacle heights. While this modeling technique helps recognize the features of the distribution of MFC data (i.e skewness and kurtosis), the method reported here may provide a pragmatic alternative for characterizing the probability of tripping. Of note, though, is that trip probabilities obtained from the two methods differed substantially. For an obstacle height of 1 cm, Best and Begg (2008) reported a trip probability of 50% (Best and Begg, 2008) whereas the current method yielded a probability of less than 5% (depending upon the specific