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2 A Short Communication resubmitted to Journal of Biomechanics titled:

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

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1 **Abstract**

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

1 **Introduction**

2 Fall-related injuries among older adults are a major public health problem due to their high
3 medical costs and negative impact on quality of life (Bruce et al., 1992). Tripping accounts for
4 35-53% of these falls (Berg et al., 1997; Blake et al., 1998). The most common measure for
5 characterizing the probability of tripping while walking is the minimum foot clearance (MFC)
6 during swing. A decrease in the central tendency (i.e. mean/median) of MFC, or an increase in
7 MFC variability, are both associated with an increased probability of tripping (Begg et al., 2007;
8 Mills et al., 2008; Winter, 1992). These indirect measures of probability of tripping, however,
9 can lead to ambiguous results when both increase or decrease simultaneously. For example,
10 Nagano *et al.* (2011) reported higher median MFC and MFC interquartile range (IQR, a measure
11 of MFC variability) during overground walking compared to treadmill walking (Nagano et al.,
12 2011), and Rossi *et al.* (2013) reported higher median MFC and MFC IQR in the non-dominant
13 leg and at faster gait speeds (Rossi et al., 2013). Median MFC and MFC IQR are also positively
14 correlated (Begg et al., 2007), indicating concurrent increases or decreases in both are to be
15 expected.

16
17 The purpose of this study was to present a method that determines the probability of tripping
18 over an unseen obstacle while avoiding the ambiguous situation wherein median MFC and MFC
19 IQR concurrently increase or decrease, and determines how the probability of tripping varies
20 with potential obstacle height. The method was used to investigate the effects of age, obesity,
21 gender, and gait speed on the probability of tripping. These factors were investigated based upon
22 reports of elevated risks of falling and fall-related injuries among adults over the age of 65
23 (Bruce et al., 1992; Kannus et al., 1999), individuals who are obese (Fjeldstad et al., 2008;

1 Himes and Reynolds, 2012; Patino et al., 2010), females (Ambrose et al., 2013; Stevens, 2005),
2 and changes in risk of tripping with gait speed (Rossi et al., 2013; Schulz, 2011).

3

4 **Methods**

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

10

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

19

[Table 1]

20 MFC values were used to create trip probability curves that indicated how the probability of
21 tripping varied as a function of height of a potential tripping obstacle (Figure 1). For potential
22 tripping obstacle heights ranging from 0 - 7 cm, in increments of 2 mm, each experimental MFC
23 value was dichotomized as either a trip (if the potential obstacle height was greater than MFC) or

1 a non-trip (if the potential obstacle height was equal to or less than MFC). The percentages of
2 trips at each obstacle height were then computed, serving as an estimate of the probability of
3 tripping.

4

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

15

16 The second step in this technique was to determine whether the actual observed difference in
17 probability of tripping between groups was statistically significant. The actual observed
18 difference in probability of tripping between groups was defined as the absolute value of the
19 difference between the group percentages at a potential obstacle height. Because each
20 bootstrapping analysis involved 36 comparisons between groups (0-7 cm obstacles heights in
21 increments of 2 mm), the significance level was $0.05/36$, or $\alpha=0.0014$, to avoid consequences of
22 type I errors. As such, if the actual difference in probability of tripping was in the outer 0.14% of
23 the distribution, then the difference in trip probability between groups was considered

1 statistically significant. Alternatively, the percentage of the distribution of differences outside of
2 the actual observed difference yielded a bootstrap p -value. This second step was performed for
3 all potential obstacle heights, and between all participant groups of interest, to determine the
4 specific heights at which the probability of tripping differed between groups.

5
6 Group differences identified from this statistical bootstrapping technique were compared with
7 group differences identified using the traditional measures of median MFC and MFC IQR.
8 Group differences in median MFC and MFC IQR were determined using a four-way, mixed-
9 factor analyses of covariance (ANCOVA) with planned contrasts. Independent variables in the
10 ANCOVAs were age, obesity, and gender, and gait speed was the covariate. Analyses were
11 performed using JMP v7 (Cary, North Carolina, USA).

12
13 **Results**

14 Age-related differences in the probability of tripping were not consistent between the
15 bootstrapping technique and the ANCOVA analysis. Among normal-weight adults (Figure 1a),
16 the probability of tripping was lower among older adults across a range of obstacle heights (2.0-
17 4.6 cm), while no age effects were found for either median MFC or MFC IQR. Among obese
18 adults (Figure 1b), the probability of tripping was also lower among older adults, but across a
19 smaller range of obstacle heights (1.2-2.4 cm), while again there were no age effects for either
20 median MFC or MFC IQR.

21 [Figure 1]
22 Obesity-related differences in the probability of tripping were also not consistent between the
23 bootstrapping technique and the ANCOVA analysis. Among older adults (Figure 1c), the

1 probability of tripping was significantly higher among obese adults across a range of obstacle
2 heights (2.4-4.2 cm), while there were no obesity effects on median MFC or MFC IQR. Among
3 young adults (Figure 1d), there were no significant effects of obesity on the probability of
4 tripping, nor on median MFC or MFC IQR. With respect to gender (Figure 1e), the probability of
5 tripping was higher among females across a range of obstacle heights (0.8-4.4 cm), while both
6 median MFC and MFC IQR were lower among females. With respect to speed (Figure 1f), the
7 probability of tripping was lower for the faster hurried speed across a narrow range of obstacle
8 heights (4.2-5 cm), while both median MFC (approached significance) and MFC IQR were
9 higher at the faster hurried speed.

10

11 **Discussion**

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

20

21 Three limitations to the method presented here warrant mentioning. First, this method, along
22 with ANOVA using median/mean MFC and MFC IQR, focuses on foot clearance at the instant
23 that MFC occurs, even though a trip could occur at other instances during the swing phase.
24 Second, unlike an ANOVA based upon median/mean MFC and/or MFC IQR, the current method

1 cannot incorporate measures of covariance, or statistically control for the effects of other
2 variables, when evaluating an independent variable of interest. Third, this method, along with
3 most other investigations of MFC, assumes individuals will not see or react to an obstacle in
4 their path. While this may be true for smaller obstacles, this is less likely for larger obstacles.

5
6 The method presented here may be helpful in ensuring that safety guidelines are inclusive and
7 protective for diverse populations. For instance, The Americans with Disabilities Act (ADA)
8 stipulates that abrupt changes in height of a walkway greater than 6 mm require edge treatment
9 to account for individuals in wheelchairs and individuals whose foot is impeded during the swing
10 phase of gait (Cohen and Abele, 2007). The results in Figure 1c indicate that trip probability does
11 not differ between normal-weight and obese older adults unless obstacle height exceed 2.4 cm,
12 suggesting that the 6 mm standard of the ADA is equally protective for both of these
13 populations.

14
15 A statistical modeling technique reported by (Best and Begg, 2008) also characterizes the
16 probability of tripping over a range of obstacle heights. While this modeling technique helps
17 recognize the features of the distribution of MFC data (i.e skewness and kurtosis), the method
18 reported here may provide a pragmatic alternative for characterizing the probability of tripping.
19 Of note, though, is that trip probabilities obtained from the two methods differed substantially.
20 For an obstacle height of 1 cm, Best and Begg (2008) reported a trip probability of 50% (Best
21 and Begg, 2008) whereas the current method yielded a probability of less than 5% (depending
22 upon the specific group of interest). This difference may be due to methodological differences

1 between the two studies including overground vs treadmill walking, walking speeds, number of
2 participants, and methods used to estimate MFC.

3
4 The method presented here identified differences in probability of tripping that provided both
5 novel and complementary insight to the literature. Regarding obesity, no studies to our
6 knowledge have reported effects of obesity on median/IQR MFC. The higher probability of
7 tripping among obese individuals found here (albeit only among older adults) may help to
8 explain the higher fall rates among individuals who are obese (Fjeldstad et al., 2008). Regarding
9 gender, lower median MFC among females reported by Rossi et al. (2013) is consistent with the
10 median MFC results presented here. However, the concurrently lower MFC IQR among females
11 also reported here obscures the net effect of these differences on probability of tripping. The
12 current method provides clear and direct biomechanical evidence that the probability of tripping
13 is higher among females. Interestingly, these results appear to align with those by Berg et al.,
14 who in a one-year prospective survey study of adults aged 60-88, found that falls among females
15 most often occurred due to tripping whereas falls among males most often occurred due to
16 slipping (Berg et al., 1997). Regarding age, the current method identified a higher probability of
17 tripping among older adults, but no age differences in median/IQR MFC. The majority of MFC
18 studies reviewed by Barrett et al. (2010) also found no age differences in median MFC, but did
19 find higher MFC IQR which suggests a higher probability of tripping among older adults (Barrett
20 et al., 2010). Thus, the results of the current method with respect to probability of tripping are
21 consistent with these findings. The present method also has the advantage of identifying the
22 specific obstacle heights at which age differences exist, which may be helpful for various trip
23 and fall prevention strategies.

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Conflict of interest statement

The authors have no conflicts of interest to report.

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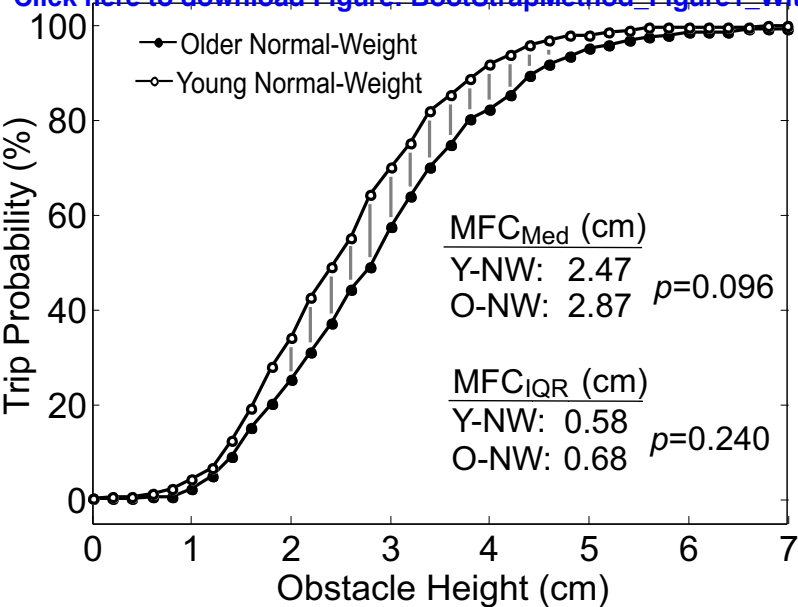
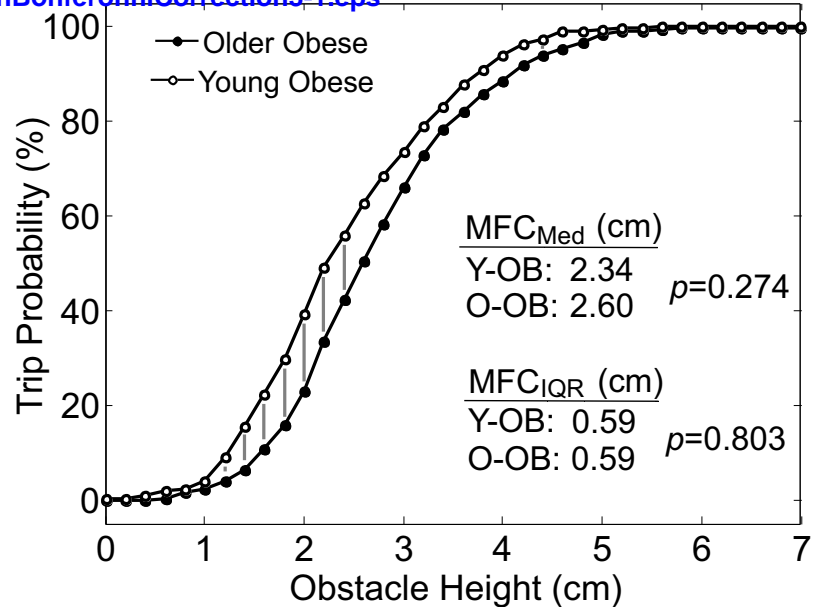
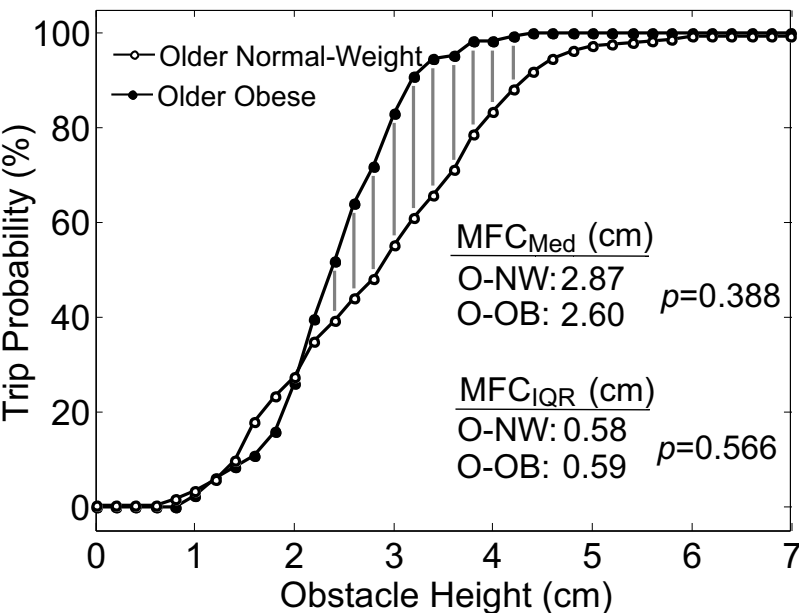
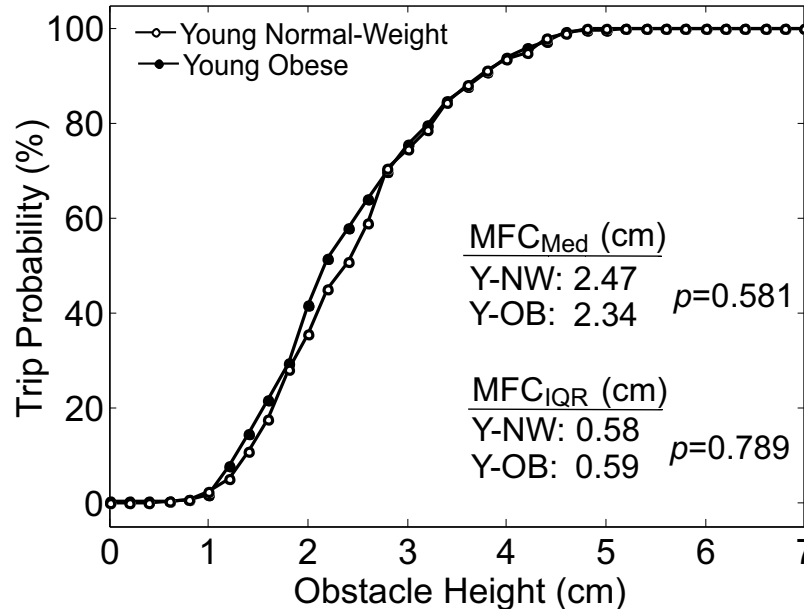
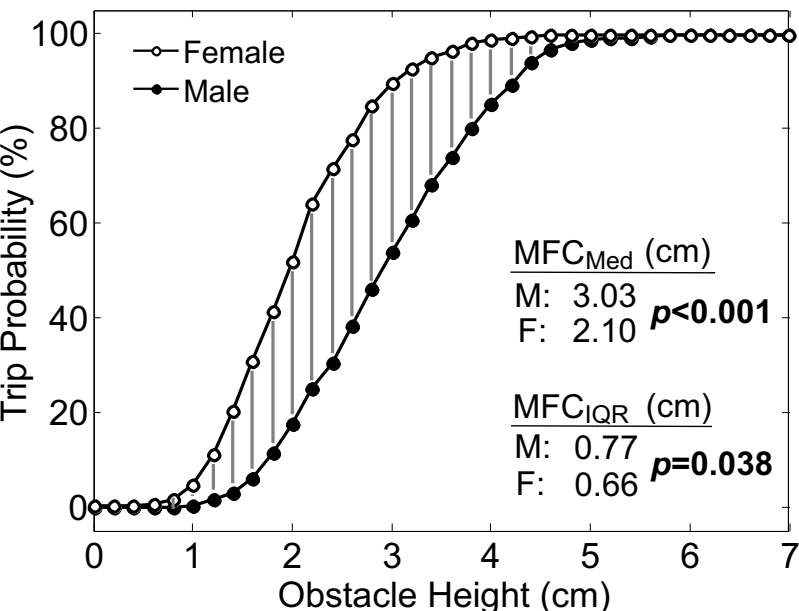
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Figure Legends

Figure 1: Trip probability curves and median/IQR MFC separated by age group, obesity group, gender, and speed. Differences in probability of tripping between groups ($p < 0.0014$) are indicated by a solid vertical line, and differences in median/IQR MFC ($p < 0.05$) are indicated by bold.

Figure 1 Normal-weight adults: older vs. young[Click here to download Figure: BootStrapMethod_Figure1_WjthBonferonniCorrection3-1.eps](#)**(b)** Obese adults: older vs. young**(c)** Older adults: normal-weight vs. obese**(d)** Young adults: normal-weight vs. obese**(e)** Male vs. female

Hurried vs. Self Selected

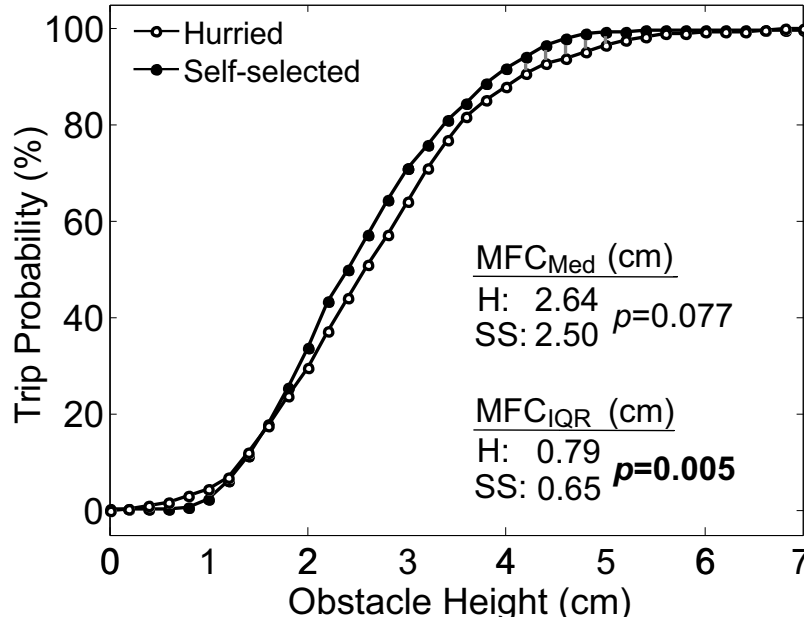


Table 1: Participant demographics (mean \pm standard deviation)

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

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

Conflict of interest statement

The authors have no conflicts of interest to report.