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Inadvertent obstacle contacts when older adults step over obstacles: Effect of sex, self-reported fatigue, gait parameters, and prescription medications

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HIGHLIGTHS
- 37% of older adults tripped on a stationary, visible obstacle in the walkway.
- Self-reported fatigue increased during walking in the 30-40 minute protocol.
- Those who tripped had higher fatigue, slower gait speed, and took more medications.
- Improving endurance is an important target for fall intervention programs.

ABBREVIATIONS
SDs Standard deviations

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BACKGROUND: Tripping is a common cause of falls, but the factors associated with trip risk are understudied. Factors that may affect trip risk include biological sex, fatigue, gait measures, and prescription medications.
AIM: To quantify inadvertent trips with a stationary, visible obstacle in older adults, and to determine if the factors (e.g., fatigue) of older adults who trip are different from those who don't trip.
METHOD: Forty-one participants walked on a 6 m walkway and stepped over a visible, stationary obstacle (height: 25% of leg length) 100 times. We documented inadvertent trips with the obstacle, gait measures on a clear walkway, self-reported fatigue every 25 obstacle crossing trials, and number of prescription medications.
RESULTS: The obstacle was contacted by 15 participants (37%) in 29 trials (0.7% of all trials); 52% of contacts were with the lead limb. Self-reported fatigue increased during the obstacle crossing protocol ($p<0.001$). Participants with ≥1 contacts had slower gait speed, shorter stride length, higher gait cycle time variability, higher fatigue ratings, and a higher number of prescription medications ($p\leq0.041$). Males and females were not different in contact frequency ($p=0.93$).
CONCLUSION: Inadvertent trips were not uncommon in older adults, even with a visible, stationary obstacle. Balance recovery from lead limb trips is difficult due to center of mass motion relative to the base of support and highlights the difficulty older adults have recovering balance after a trip. The significant association between fatigue (induced by walking) and impaired gait is highly relevant when quantifying gait in older adults, and also when developing fall prevention programs.

KEYWORDS: Adaptive gait | Fall risk | Gait variability | Gait speed | Obstacle crossing

INTRODUCTION

Falls are the number one cause of both fatal and non-fatal injuries among older adults [1]. Falls can be caused by a variety of events such as slipping, a misstep, loss of support, or tripping [2]. Trips cause 34-53% of falls in community-dwelling older adults [3,4]. Injuries associated with tripping increase with age as follows: Males increased from 8% to 12% to 19% and females increased from 17% to 21% to 23% for age groups 18-44, 45-64, and 65+ years, respectively [2]. Therefore, quantifying trip-related behavior in older adults is important to increase knowledge regarding the factors associated with trips. *Reactive* recovery from trips is quantified with covert obstacles that unexpectedly arrest the forward motion of the swinging limb [5,6]. *Proactive* gait adaptations are quantified with stationary, visible obstacles in the walkway [7,8]. In proactive research, healthy adults occasionally contact the stationary obstacle (referred to as inadvertent trips); these trials are typically discarded. With normal vision and full lighting, inadvertent trips occur in 1-2% of trials summarized in (Muir and colleagues [9]). Since inadvertent trips occur in a controlled setting, they provide a unique opportunity to observe the circumstances of tripping and to quantify how various factors are associated with trips.

When a young adult trips on a visible and stationary obstacle, they trip with the trail limb 86-92% of the time, where the trail limb is the second limb to cross the obstacle [9,10]. Conversely, older adults have more trips with the lead limb (67% of trips [9]). Lead limb trips, relative to trail limb trips, pose a greater threat to balance since the center of mass is beyond the stance limb and moving forward, drastically reducing the time for corrective action [9,10,11]. The greater threat from a lead limb trip is also evident from the multiple steps generally needed to recover from the trip, while normal gait was generally resumed in the step following a trail limb trip [11]. Thus, older adults may be less likely to recover their balance after tripping since they appear to be more likely to trip with the lead limb than young adults [9]. However, the 67% lead limb trips in older adults resulted from a secondary analysis of an existing dataset, and thus only three older adults were included in this analysis [9]. Therefore, it is important to determine if the higher number of lead limb trips observed in a small number of participants [9] is also evident with larger numbers of participants.

Given that trips are a frequent cause of falls and fall-related injuries [2,3,4], multiple factors associated with falls (i.e., biological sex, gait parameters, fatigue, and prescription medications) [3,4,12,13] are also likely associated with trip-risk. Regarding sex, older females have more than twice as many trip-related injuries as older males, and trips accounted for more injuries in older females than older males [2]. Gait parameters that have been associated with falls include: speed, step length, step width, and/or variability of these measures [12,14,15]. Exercise-induced fatigue increases lower limb variability, impairs motor control [16,17], and increases trips on obstacles in relatively young firefighters [18,19,20]. Furthermore, the effect of exercise-induced fatigue on movement was greater in adults aged 40 and older compared to younger participants during level walking and obstacle crossing [17]. However, fatigue may also increase when older adults walk, but it is unknown if walking-induced fatigue increases trips. Prescription medications are associated with fall-risk and may be associated with inadvertent trips as well, possibly due to side effects including blurred vision, impaired depth perception, and/or other visuomotor skills [21,22].

The purposes of this study were (1) to quantify the frequency and circumstances (lead versus trail limb) of inadvertent trips in adults aged 65 and older, and (2) to determine if older adults who trip are different from those who do not trip for the following factors: sex, gait parameters, walking-induced fatigue, and prescription medications). Note that in contrast to studies that induce fatigue through fatiguing protocols (for example, repeated sit-to-stand 30 times per minute until fatigued [17]), here we quantified the fatigue that participants reported before, during and after the walking and obstacle crossing trials (30-40 minutes of walking, with rest breaks every 5-8 minutes). We hypothesized that ≥32% of the inadvertent trips would occur with the lead limb (H1). This would mean that, when the obstacle was contacted, older adults contacted with the lead limb four times more often than young adults (lead limb contact occurred in 8% of contact trials in young adults, [10]). We hypothesized that females would have a higher frequency of trips than males (H2). We hypothesized that the older adults who tripped would have slower, more variable gait with shorter step lengths (H3), higher self-reported fatigue (H4), and a higher number of prescription medications (H5).

METHODS

Participants

Forty-one older adults (age: 76.6 + 6.9 years, 25 females) participated. Participants walked without an aid, had no orthopedic or neuromuscular disorders (as verified by self-report), and were independent in daily activities. Participants wore their prescribed corrective lenses for all testing, including vision testing. Participants were screened for cognitive impairments using a clock-drawing test [23], and for visual acuity using a Snellen chart (required visual acuity: 20/40 or better). All participants signed an informed consent approved by the Institutional Review Board.

Protocol

Participants completed two gait tasks, unobstructed gait and obstacle crossing gait, and reported their fatigue at specified intervals during the protocol (Figure 1). The participants walked for a total 30-40 minutes (including rest breaks); total distance walked was 1.29 km (0.8 miles). Participants were asked not to talk during the gait tasks, as it is known that talking alters walking behavior [24,25].

Unobstructed Gait (steady state gait): Participants walked on a 15 m clear walkway, turned around, and walked back to the start (Figure 1). Unobstructed gait was assessed three times: at the beginning, after 50 obstacle crossing trials, and after 100 obstacle crossing trials. Gait measures were recorded with two wireless inertial measurement units (GaitUp, Physilog, Lausanne, Switzerland); one unit was placed on each foot.

Obstacle Crossing: Participants walked on a 6 m grey Berber carpet (a tightly woven loop pile, with low pile height), stepped over an obstacle placed at 4 m, continued to the end of the carpet, and returned to the start position without stepping over the obstacle (Figure 1). Subjects self-selected which foot would cross the obstacle first. The obstacle height was 25% of the subject's leg length. This height was selected to allow comparison with published research on young adults [10] and because higher numbers of contacts are observed with taller obstacles [26,27,28,29]. Obstacle height range: 19.5-26 cm, in 0.5 cm increments; 100 cm wide, 0.3 cm deep. The obstacles were made of Masonite and painted flat black. To reduce risk of falling, obstacles were designed like a hurdle to tip over if contacted, and an experimenter spotted participants using a gait belt. Participants were instructed "Occasionally a person contacts the obstacle. If you contact the obstacle, it will fall over like a hurdle. Please continue walking and we will pick it up." If an obstacle contact occurred, two experimenters independently recorded the trial number and the contact foot (lead or trail: first or last limb to cross the obstacle). The participant's lower limbs were videotaped during obstacle crossing to confirm obstacle contacts offline. Obstacle crossing was completed in four blocks of 25 trials each (Figure 1), with a 2-minute break after each block.

Self-reported fatigue was assessed with the rating-of-fatigue scale [30]. The rating-of-fatigue scale describes fatigue level in three different formats: numerical (0-10), descriptive (words), and diagrammatic (line drawing of person). The corresponding formats are presented together. For example, the number 0 corresponds to the descriptive 'not fatigued at all' and to a drawing of a person with eyes wide open, standing with arms high in the air. The numerical 10 corresponds to 'total fatigue and exhaustion – nothing left' and a drawing of a person lying prone with their eyes closed. The scale has high convergence with physiological measures (e.g., heart rate, blood lactate concentration, oxygen uptake) [30]. Rating-of-fatigue was assessed five times during the protocol: at the beginning before any walking trials and at the end of each block of 25 obstacle crossings (during the scheduled rest break).

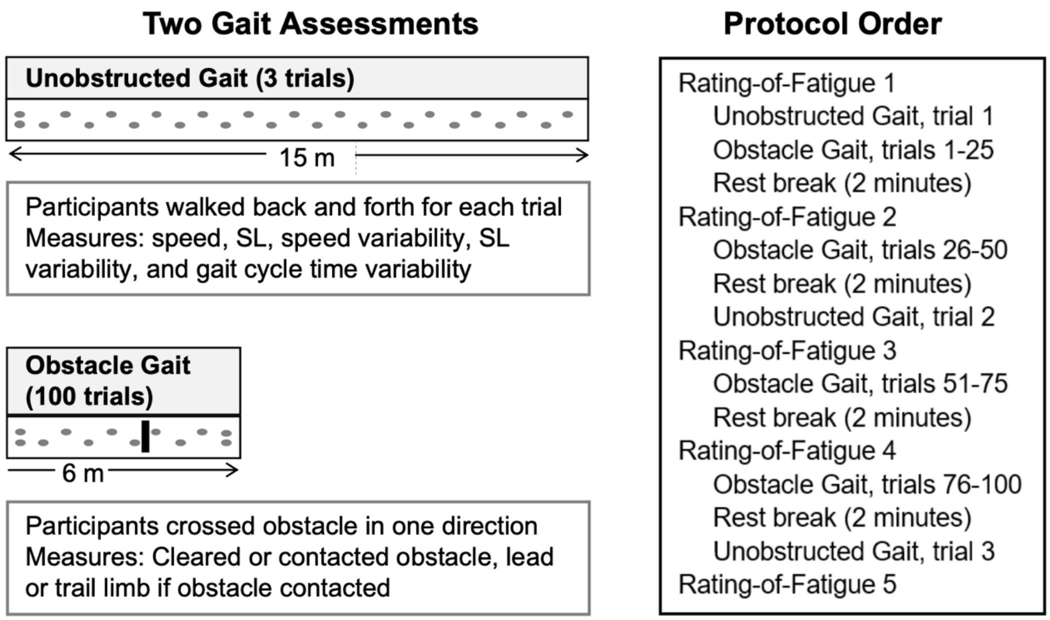

Figure 1. Depiction of two gait tasks (unobstructed gait and obstructed gait) and the protocol order. Gray ellipses indicate approximate footsteps during gait tasks.

Data Analysis

Unobstructed Gait Measures were assessed with GaitUp. Trials were filtered to remove turns, the first two steps, and the last two steps [31]. A filter was applied to remove data points that were 2 standard deviations (SDs) higher or lower than the median value [32]. Five gait variables were assessed during the unobstructed walking trials: stride speed, stride length, stride speed variability, stride length variability, and gait cycle time variability. Variability was quantified as the coefficient of variation (standard deviation/mean x 100) [33].

Obstacle crossing measures included trial number of contact and the contact limb (lead or trail). The two experimenters had 100% agreement on the contact trials and contact limbs. The contacts and contact limb were later confirmed by video, demonstrating 100% agreement with in-person observation.

Group Categorization: Participants were categorized into two groups: 0 contacts or ≥1 contact.

Statistics: Two-sample independent t-tests were used to compare the two groups for the following: five gait measures, highest reported fatigue, and age. A Wilcoxon rank sum test was used to compare the two groups for number of prescription medications. To determine if fatigue rating increased during data collection, a one-way ANOVA (five levels: 0, 25, 50, 75, 100 trials) was completed. A Kenward-Roger correction was applied to account for missing fatigue data in the last block for the participant who stopped at trial 75. Posthoc comparisons were completed with a Tukey adjusted for multiple comparisons. We excluded people with vision worse than 20/40, but since there was still a range in visual acuity scores, we also determined if the two groups were different in visual acuity with a chi square test. Significance level was set to $p \leq 0.05$. Statistical tests were done with SAS version 9.4 (ANOVA) and R version 3.6.1 (remaining tests).

RESULTS

During unobstructed gait, equipment error prevented gait data collection in two participants; thus, these two participants were not included in the analyses for unobstructed gait parameters. Neither participant contacted the obstacle during obstacle crossing. However, we included them in the description of obstacle contacts. If we excluded them, it would have a limited effect on the percentage of participants who never contacted the obstacle (a decrease from 63% to 62%). All subjects completed 100 obstacle crossing trials, with one exception: One participant completed 75 trials and then stopped due to a combination of fatigue and a prior commitment. He tripped 4 times, and thus was coded as ≥1 contact. His data was included in all analyses.

Obstacle Contacts

The obstacle was contacted 29 times (0.7% of 4075 trials); 15 participants had one or more obstacle contacts (37% of 41 participants) (Figure 2). Of the 29 obstacle contacts, 52% occurred with lead limb. The median trial number of the first obstacle contact was trial 40 (interquartile range: 12-73), the median trial number for all obstacle contacts was trial 72 (interquartile range: 33-78). Frequency of obstacle contact was not affected by sex (OR (95% CI): 1.07 (0.27 - 4.24); p = 0.93; Table 1).

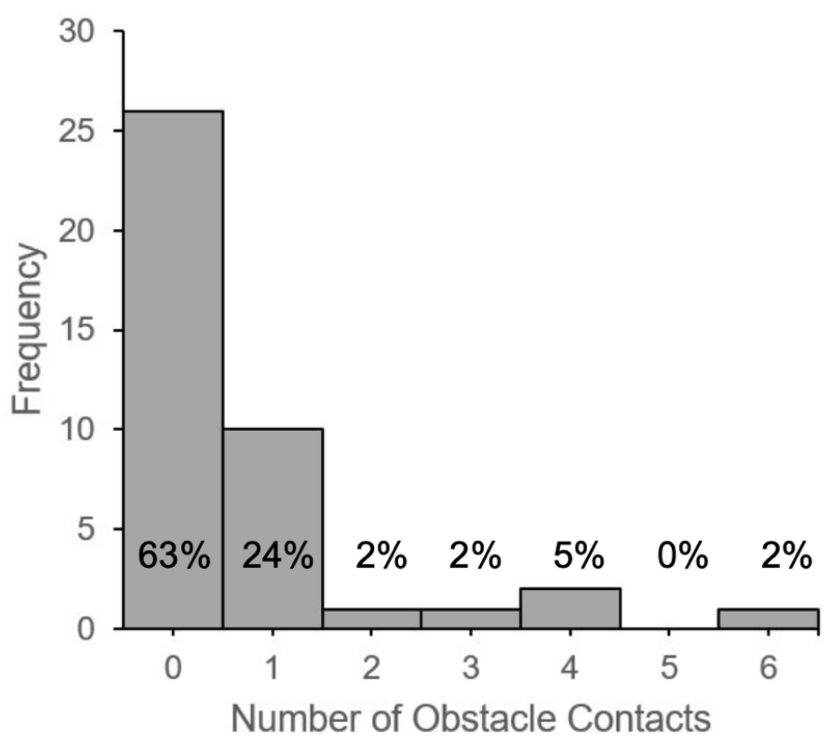

Figure 2. Histogram of number participants versus the number of obstacle contacts. Percent of participants in each category indicated above horizontal axis.

Table 1. Distribution of trips (obstacle contacts) in males and females

Sex	Age [95% CI]	Percent with ≥1 contact	Number of obstacle contacts	Percent of trials with contacts
Female (n = 25)	76.8 [6.2]	36% (n = 9)	19	0.8
Male (n = 16)	76.3 [8.1]	38% (n = 6)	10	0.6
Total (n = 41)	76.6 [6.9]	37% (n = 15)	29	0.7

The two groups (0 contacts vs ≥1 contact) were not different for age (p = 0.27; Table 2) or visual acuity (p = 0.66). Number of prescription medications was higher for participants with ≥1 contact compared to 0 contacts (mean: 4.6 vs 2.3, respectively; W = 108.5; p = 0.02).

Stride length, stride speed, gait cycle time variability, and highest reported fatigue were different for participants with ≥1 contact compared to 0 contacts (p ≤ 0.04; Table 2).

Table 2. Age, unobstructed gait variables, and fatigue in the 0 contact group vs ≥1 contact group

Variable	0 contacts [95% CI] (n=24)	≥1 contact [95% CI] (n=15)	*p*-value	Cohen *d*
Age (years)	75.7 [2.2]	78.5 [5]	0.273	0.42
Stride Speed (m/s)	1.19 [0.13]	1.06 [0.16]	**0.013**	**0.93**
Stride Length (m)	1.27 [0.13]	1.16 [0.13]	**0.016**	**0.84**
Stride Speed Variability (%)	6.14 [2.31]	6.32 [1.87]	0.792	0.08
Stride Length Variability (%)	4.76 [1.49]	5.06 [1.28]	0.521	0.21
Gait Cycle Variability (%)	2.59 [0.69]	3.18 [0.92]	**0.041**	**0.77**
Highest Reported Fatigue	3.12 [0.60]	4.73 [1.38]	**0.035**	**0.83**

Fatigue rating increased as number of obstacle crossing trials increased ($F(4,167) = 45.33$, $p < 0.001$, Cohen d = 1.15; Figure 3). Post hoc tests revealed that the fatigue rating increased significantly from trial 0 to trial 25 ($p < 0.001$, Cohen d = 0.58), and then increased significantly for every 50 trials after the 25^{th} trial (i.e., fatigue at trial 25 was not different from trial 50, but was lower than trial 75 ($p < 0.001$, Cohen d = 0.54), and fatigue at trial 50 was lower than trial 100 ($p < 0.001$, Cohen d = 0.40). Thirty-six participants (88%) reported an increase in their fatigue rating compared to their initial fatigue rating. For qualitative comparisons, participants with highest reported fatigue ≥3 out of 10 (n = 26) during any time interval were compared to those with ratings always <3 (n=15) (Figure 4). Participants with higher fatigue ratings were more than twice as likely to contact the obstacle.

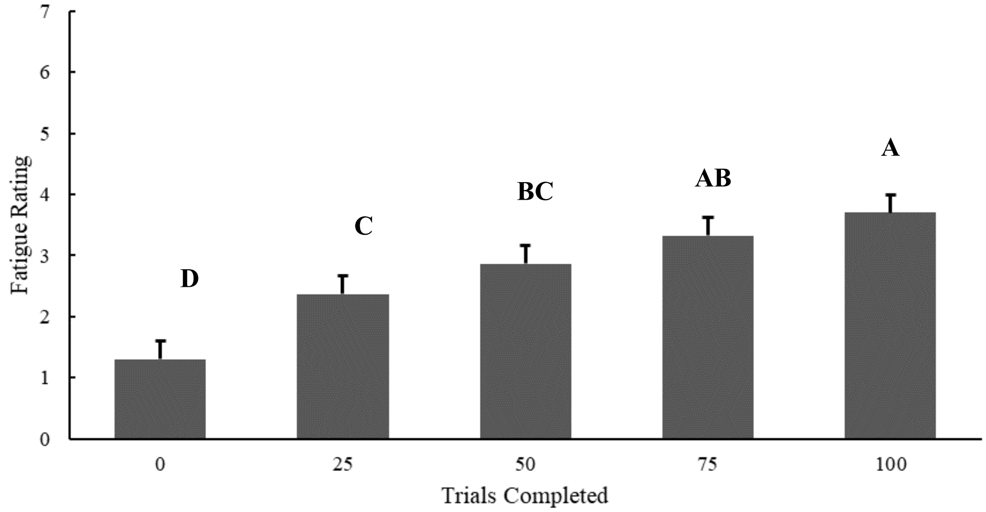

Figure 3. Fatigue rating as a function of obstacle crossing trials completed. Error bars are standard error. Different letters (A, B) indicate statistically significant differences. For example, A is different from BC and C, but A is not different from AB.

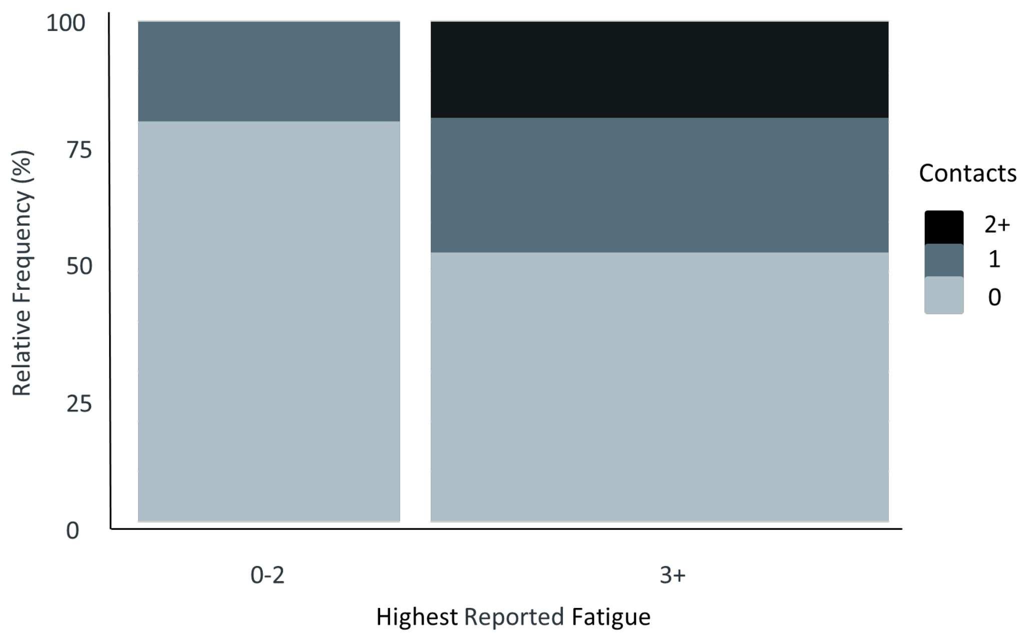

Figure 4. Mosaic plot of the relative frequency of obstacle contacts as a function of the highest reported rating of fatigue of each participant. The width of each rectangle is proportional to the number of participants within that group.

DISCUSSION

The purposes of this study were (1) to quantify the frequency and circumstances (lead versus trail limb) of inadvertent trips in adults aged 65 and older, and (2) to determine if older adults who trip are different from those who do not trip for the following factors: sex, gait parameters, walking-induced fatigue, and prescription medications. We emphasize that the trips observed in this study were not induced by unexpected perturbations (e.g., covert obstacle [5,6]), by manipulating visual information (e.g., liquid crystal goggles [34]), or by directly manipulating factors such as foot placement [26]. Rather, the trips occurred when stepping over a stationary, visible obstacle, and thus are likely more similar to those observed during daily activities. Current knowledge was extended using an obstacle crossing protocol that (1) quantified inadvertent trips in older adults under standardized conditions, and (2) examined factors associated with inadvertent trips, such as unobstructed gait characteristics. We observed that inadvertent trips were not uncommon in older adults (37% of participants tripped at least once), and that 52% of contacts occurred with the lead limb. We accepted the hypotheses that inadvertent trips were associated with unobstructed gait parameters (stride speed, stride length, and gait cycle time variability), self-reported fatigue, and number of prescription medications. However, inadvertent trips were not associated with sex.

Inadvertent trips were not uncommon in older adults, and their occurrence was similar to that observed in young adults in previous research [10]. To allow comparison with the older adults collected here, we truncated the observations in the young adult data to the first 100 trials (the young adult protocol included ≥250 obstacle crossing trials, [10]). There were marked similarities across age: 40% vs 37% (young vs older adult participants, respectively) tripped at least once during 100 obstacle crossing trials, and 0.6% vs 0.7% (young vs older adult, respectively) of 100 obstacle crossing trials included an inadvertent trip. We emphasize that both studies included healthy participants in a controlled setting: good lighting, a black obstacle designed to tip if contacted with height set to 25% leg length, grey Berber carpet, no talking allowed during gait tasks, spotter present, and people with impaired vision were excluded. Differences across studies included: 6 m vs 8 m walkway, IMUs on feet vs infrared-emitting diodes placed on feet and head, self-reported fatigue assessment vs no fatigue assessment, clear walkway trials vs no clear walkway trials (older vs young protocol, respectively).

Comparison of the current study with the previously published young adult trip study [10] provides new insight about age-related and sex-related effects on trips over obstacles. Interpretation of research examining trip-related falls must consider the following: First, did the person trip or not? Second, if they did trip, did they recover their balance or did they fall? Third, if they fell, were they injured? Research based on medical reports addresses the third question: injuries associated with trips increase with age and are greater in women than men [2], but it is unknown if older adults trip more, or are less likely to recover balance (i.e., the first two questions). Since we ensured people would not fall or be injured in our protocol, our study can only address the first question: Did the person trip or not? Our observations do not support the idea that older adults are more likely to trip than young adults under conditions of normal lighting with a high contrast obstacle without distractions. Similarly, our observations do not support the idea that older adult females are more likely to trip than older adult males under the controlled conditions of our protocol. In other words, older adults relative to younger adults, and older females relative older males, appear to be have similar sensory ability to detect high contrast obstacles and have sufficient motor capabilities to step over them successfully. Rather, the differences in fall-related injuries [2] may result from factors such as: less likely to recover balance after a trip [35], more likely to be injured from a fall due to age-related factors such as osteoporosis [36], poor lighting or other factors that may impair visual information more for older adults, and distracted attention [37]. Lab-based protocols have found that older females are four times more likely to fall as males when trips are induced using a concealed mechanical obstacle [6]. This may be partially explained by women having less muscle mass and a longer reaction time than men [38,39]. It is also possible that females spend more time in environments where trips are more likely to occur. Understanding these differences and obtaining more information about the circumstances of trips will likely be relevant for developing effective interventions to prevent trip-related falls in older adults and, especially, older females.

Fifty-two percent of the contacts in older adults occurred with lead limb, which increases the risk of falling [7,9,10,29]. In comparison, previous research indicates that younger adults rarely trip with the lead limb (8% of contacts) [10]. Thus, while trip frequency was similar for young and older adults, older adults were six times more likely to trip with the lead limb. As noted in the introduction, lead limb trips pose a greater threat to balance because the center of mass is moving away from the base of support (stance foot is behind the obstacle); conversely, during a trail limb trip, the center of mass is moving towards the base of support (stance foot is in front of the obstacle) [9,11]. Since lead limb trips are more likely to result in a fall, the higher frequency of lead limb trips observed in older adults may explain why a greater percentage of fall-related injuries are caused by trips in older adults when compared to other age groups [2] and emphasizes the importance of continued research on inadvertent trips in older adults.

The increased proportion of lead limb contacts for older adults is likely related to an age-related decrease in step length [7,9,29,40]. Despite the shorter step length, older adults' trail foot placement prior to obstacle crossing is the same as young adults' trail foot placement [7,28,29,41]. Since the placement of the trail foot is the same, the shorter step length in older adults results in closer foot placement after obstacle crossing, increasing the risk of lead limb contacts [7,9]. Although normally rare in young adults, lead limb trips are more frequent when vision is obstructed or distorted [34,42,43]. Unlike the trail limb, visual guidance is available while crossing with the lead limb so it is logical that visual manipulations result in an increase in the proportion of lead limb trips [10,27,44]. Thus, research should examine the idea that the higher proportion of lead limb trips observed in older adults may, at least in part, reflect an impairment of older adults' visual guidance of the lead limb trajectory. Visual acuity is likely not linked to the lead limb trips we observed since we excluded participants with visual acuity worse than 20/40 and visual acuity was not different across the two groups. Similarly, previous research found that visual acuity and edge contrast were not significant determinants of obstacle contacts, but depth perception was [45]. There is also a growing body of evidence that interventions aimed at improving eye and stepping coordination have a positive effect on stepping control and reducing falls risk [46].

Gait measures on a clear walkway were related to inadvertent trips, consistent with the relationship between gait characteristics and falls during everyday activities [12,14,15,47,48]. Participants with one or more obstacle contacts had slower stride speed, shorter stride length and higher variability in gait cycle time compared to participants with no obstacle contacts, similar to the association between gait parameters and fall-risk [12,14,47,48]. Stride speed was 11% slower in people with ≥1 contacts (Table 2), likely for the same reasons slower speed is associated is associated with higher fall-risk [49]: Gait places demands on multiple organ systems, including sensory, motor, and cognitive systems. A change in any of those systems may increase the risk of tripping and/or falling and will also be evident as reduced speed. As noted above, the 9% shorter step length (Table 2) increases the risk of obstacle contact due to foot proximity to the obstacle. Gait cycle time was 23% more variable in people with ≥1 contacts, consistent with a systematic review that observed that variability of temporal measures provided the best discrimination (relative to other linear measures) between fallers and non-fallers [48]. Higher gait variability in older adults who are more likely to trip may be associated with changes in cortical and subcortical brain areas, and supports the view that gait variability provides a biomarker of organic integrity [50].

Inadvertent trips were also associated with the number of prescription medications, similar to the association between falls and number of prescription medications [13,51]. Medications are likely associated with trip-risk because they are a proxy for the person's underlying health status, and/or the drug directly impairs coordination and movement. Therefore, the current results support continued efforts to identify the cost-benefit of deprescribing medications to prevent falls [51].

Self-reported fatigue was associated with impaired ability to safely negotiate obstacles in older adults, consistent with the effect of experimentally induced fatigue: increased lower limb variability and impaired motor control [16,17] and increased trips on obstacles in relatively young firefighters [18,19,20]. The fatigue induced in this protocol from walking and stepping over obstacles for 1.29 km is likely similar to the fatigue induced from everyday activities, such as a shopping trip. Overall, the association between walking-induced fatigue and inadvertent trips highlights the importance of measuring fatigue in future gait studies. Furthermore, endurance training should be considered as a potential intervention for people who trip frequently.

This study had several limitations. First, repeatedly stepping over the same obstacle is not a situation typically encountered. However, during community mobility, clear straight walkways are seldom encountered. Rather, people encounter multiple hazards, such as ramps, curbs, stairs, etc.[52], and the repeated accommodations to these hazards likely generate similar changes to walking-induced fatigue as observed here. Second, obstacle avoidance may not have been prioritized since safety was not threatened due to the presence of a spotter and the obstacle easily collapsing if contacted. Thus, we may have observed a higher frequency of contacts than might be observed with a rigid obstacle and without a spotter present. Similarly, no other additional factors were examined that may distract the participant from the obstacle task, such as a cognitive task. Future studies should include these factors. Third, the rating-of-fatigue scale does not differentiate subtypes of fatigue, such as cognitive fatigue, psychological fatigue, and physical fatigue, or state and trait fatigue [53]. Thus, we cannot determine if one fatigue subtype is more associated with trips than others. Fourth, we only quantified the frequency of inadvertent contacts, we did not examine gait behavior or neural measures during obstacle crossing (e.g., cortical activity). Equipment use was minimized in order to reduce data collection time and thus facilitate participant recruitment; we believe that this initial study benefited from greater numbers of participants versus more data from a smaller number of participants. Future studies should address these limitations.

CONCLUSION

In summary, inadvertent trips were not uncommon in older adults. These obstacle contacts share many of the same risk factors associated with falls during everyday activities. We also found that when the task and environment are held constant, the frequency of inadvertent trips was not different in males versus females, which suggests other factors are responsible for why females have a higher proportion of trip-related injuries. Fatigue was an important factor for successful obstacle crossing and points to benefit of endurance training to preventing trips.

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