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Age differences in the required coefficient of friction during level walking do not exist when experimentally-controlling speed and step length

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Abstract

The effects of gait speed and step length on the required coefficient of friction (COF) confounds the investigation of age-related differences in required COF. The goals of this study were to investigate whether age differences in required COF during self-selected gait persist when experimentally-controlling speed and step length, and to determine the independent effects of speed and step length on required COF. Ten young and ten older healthy adults performed gait trials under five gait conditions: self-selected, slow and fast speeds without controlling step length, and slow and fast speeds while controlling step length. During self-selected gait, older adults walked with shorter step lengths and exhibited a lower required COF. Older adults also exhibited a lower required COF when walking at a controlled speed without controlling step length. When both age groups walked with the same speed and step length, no age difference in required COF was found. Thus, speed and step length can have a large influence on studies investigating age-related differences in required COF. It was also found that speed and step length have independent and opposite effects on required COF, with step length having a strong positive effect on required COF, and speed a weaker negative effect.

Keywords

aging; gait; locomotion; slipping; ground reaction forces

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Introduction

Falls are a major cause of injury and death among older adults. About 40% of community-dwelling adults age 65 and older fall each year, and the incidence of falls rises as age increases.[1] In addition, rates of injury and death related to falls increase with age[1,2] such that three quarters of deaths due to falls occur in people age 65 and over.[1] Slipping is the second most common cause of falls among older adults in cases of fall-related injury, accounting for about 21% of cases.[3] Thus, understanding the factors that contribute to slipping among older adults is important in the prevention of these falls.

The required coefficient of friction (COF), or utilized coefficient of friction, quantifies the minimum static friction necessary to prevent the foot from slipping,[4,5] and is calculated as the ratio of shear to vertical components of the ground reaction force (GRF). Understanding age-related changes in required COF may be important in reducing the incidence of slip-related falls among older adults. However, the nature of age effects on required COF remains uncertain. One study of walking on level surfaces reported lower required COF among older adults compared to young adults,[6] while others have reported no differences between older and young adults.[4,7–9] However, older adults tended to walk at a slower speed[6–9] and/or step length[8,9] compared to young adults, which could confound the identification of age differences in required COF.

Gait speed and step length influence the required COF and the shear and vertical components of the GRF. For example, required COF increases with increased step length,[4,10] and some authors have noted an expectation that gait speed should influence required COF as well.[5,8] Powers et al.[11] showed required COF increasing with increased speed, although increased speed was also accompanied by increases in step length. Thus, the effect of speed on required COF independent of step length remains unknown.

Based upon the incomplete understanding of how age, gait speed, and step length affect required COF, this study had two goals. The first goal was to investigate whether age differences in required COF during self-selected gait persist when experimentally-controlling speed and step length. The second goal was to determine the independent effects of speed and step length on required COF. Accomplishing these goals will provide fundamental information on how age, gait speed and step length affect required COF. It was hypothesized that 1) age differences in required COF would not persist when controlling both speed and step length, 2) increasing speed while holding step length constant would increase required COF, and 3) increasing step length while holding speed constant would increase required COF.

Methods

Twenty healthy adults participated including ten young adults (mean±standard deviation: age = 23.9±3.3 years, mass = 61.7±7.3 kg, height = 1.65±0.09 m) and ten older adults (mean age = 80.3±4.0 years, mass = 65.2±10.5 kg, height = 1.63±0.08 m). There were no differences between groups in mass ($p = 0.396$) or height ($p = 0.640$ m), and each age group included five males and five females. All participants were free of self-reported neural or musculoskeletal disorders that would affect balance or walking. The project was approved by the Virginia Tech Institutional Review Board, and written informed consent was obtained from each participant prior to participation.

Testing involved participants walking along an 8 meter level, dry walkway covered in a low-height loop-style carpet under five gait conditions. The gait conditions included self-selected gait and four controlled gait conditions. The self-selected gait condition involved participants walking along the walkway with no instruction with respect to speed or step length. The first two controlled gait conditions controlled speed, but not step length, and involved participants walking at either 1.1 m/s (Slow) or 1.5 m/s (Fast). These speeds were chosen as representative of the range of speeds used by both younger and healthy older adults in self-selected gait reported in the literature.[12–17] Speed control was achieved by having participants match speed with a moving belt placed alongside the walkway (Figure 1). The second two controlled gait conditions controlled both speed and step length (Slow-Constrained and Fast-Constrained). The two speeds were the same as the Slow and Fast conditions, and the controlled step length was 0.65 m at both speeds. This step length represents a mid-range value for step lengths chosen by young and older adults during self-selected gait reported in the literature.[13–18] Step length was controlled by having participants step on markings on the walkway (Figure 1). All participants wore their own but similar soft-soled, closed-toe walking shoes.

The self-selected condition was performed first, followed by the four controlled gait conditions presented to each participant in a random order. Participants were allowed practice trials to ensure they were comfortable with the task in each case. For trials without controlled step length, the starting position of the participant was adjusted iteratively during practice trials so they would naturally step on the force platform without altering their chosen gait. Three trials of each controlled gait condition were recorded to increase the likelihood that a trial closely matching the target condition(s) would be recorded. Participants stepped on a six degree-of-freedom force platform (Advanced Mechanical Technology Inc., Watertown, MA) with their right foot during each trial, and ground reaction forces were sampled at 1000 Hz. Force platform data were low pass filtered at 20 Hz (4th order zero-phase-lag Butterworth filter) prior to further analysis. The motions of reflective markers placed on the left and right heel and right anterior superior iliac spine were sampled at 100 Hz by a VICON 460 motion analysis system (VICON Motion Systems Inc., Lake Forest, CA).

For each trial, speed, step length, and peak required COF were determined. Speed was determined as the average forward speed of the right anterior superior iliac spine marker, and step length as the average forward distance between the heel markers during double stance phase. Required COF was determined by dividing the total shear GRF (resultant of anterior-posterior and medial-lateral force components) by the vertical GRF throughout stance phase, and identifying the peak in this ratio at about 10–20% stance time[19] (Figure 2) when the foot is supporting the majority of body weight, and when the foot would tend to slip forward. A forward slip of the foot at this point of the gait cycle is thought to be particularly dangerous[20] because it can be difficult to recover from, and thus lead to a fall.

Large values of required COF that occurred at the beginning and end of stance phase due to small values of vertical GRF were considered spurious and ignored.

Required COF was analyzed using two analyses. For self-selected gait, independent *t*-tests were used to investigate differences between age groups. For the controlled gait conditions, planned contrasts after a two-way mixed-model analysis of variance were used to investigate differences between age groups when controlling speed and step length, and to investigate the independent effects of speed and step length on required COF. This two-way analysis of variance had independent variables of age group (young or older) and gait condition (Slow, Slow-Constrained, Fast, Fast-Constrained). Effects of age and gait condition on speed and step length were examined using the same analysis. The first hypothesis would be accepted if required COF differed between age groups during self-selected gait (analyzed using the independent *t*-test) and *not* differ between age groups when controlling both speed and step length (analyzed using planned contrasts between age groups for Slow-Constrained and Fast-Constrained conditions). The second hypothesis would be accepted if required COF increased between Slow-Constrained and Fast-Constrained conditions (analyzed using planned contrasts within each age group). The third hypothesis would be accepted if required COF increased between Fast and Fast-Constrained (analyzed using planned contrasts within each age group).

Results

Required COF ranged from 0.124 to 0.279 for all participants and gait conditions, with an overall mean of 0.193±0.035 (Figure 3). During self-selected gait, required COF was 13.7% lower among older adults than young (p = .031), speed did not differ between age groups (p = .162), and step length was 7.5% shorter among older adults than young (p = .019). When speed was controlled but step length was not (Slow and Fast conditions), required COF was 13.8% lower among older adults across both gait conditions (Slow: 15.4% difference and p = .030; Fast: 12.4% difference and p = .053), and step length was 5.9% shorter among older adults across both gait conditions (Slow: 6.3% difference and p = .003; Fast: 5.6% difference and p = .002). When both speed and step length were controlled (Slow-Constrained and Fast-Constrained conditions), required COF did not differ between age groups (Slow-Constrained: p = .357; Fast-Constrained: p = .941).

To investigate the independent effects of speed on required COF, required COF was compared between Slow-Constrained and Fast-Constrained gait conditions within each age group. These gait conditions differed in speed (Slow-Constrained = 1.185 m/s across both groups; Fast-Constrained = 1.526 m/s across both groups; p < .001), but not in step length (Slow-Constrained = 0.650 m across both groups; Fast-Constrained = 0.654 m across both groups; p = .635). Young adults exhibited no effect of speed on required COF when maintaining constant step length (p = .436), and older adults exhibited an 8.8% lower required COF during Fast-Constrained compared to Slow-Constrained (p = .014). To investigate the independent effects of step length on required COF, required COF was compared between Fast and Fast-Constrained within each age group. These gait conditions differed in step length (Fast = 0.763 m across both groups; Fast-Constrained = 0.654 m across both groups; p < .001), but not in speed (Fast = 1.523 m/s across both groups; Fast-

Constrained = 1.526 m/s across both groups; $p = .772$). Young adults exhibited 33.0% higher required COF when walking with longer steps during Fast compared to Fast-Constrained ($p < .001$), and older adults exhibited 15.8% higher required COF when walking with longer steps during Fast compared to Fast-Constrained ($p < .001$).

Discussion

The first goal of this study was to investigate whether age differences in required COF during self-selected gait persisted when controlling speed and step length. Results from previous research with respect to age differences in required COF are ambiguous due to inconsistent findings, and potentially confounding differences in gait spatio-temporal characteristics between age groups.[6–9] It was hypothesized that age differences in required COF would not persist when controlling both speed and step length. Our results showed, consistent with prior studies, age differences in required COF during self-selected gait. These differences persisted when controlling speed, but were not found when controlling both speed and step length. As such, we accepted our hypothesis. These results confirm that investigations of age-related differences in required COF can be confounded by speed and step length, and that it is important to account for these gait characteristics when trying to understand the underlying factors contributing to any age-related differences in required COF (or lack thereof). Based upon these results, older adults appear to have a lower likelihood of slipping while walking compared to young adults, and this lower likelihood is due to age-related alterations in speed and step length. Our results also suggest that the increased rate of falls among older adults is not due to a greater likelihood of slipping while walking.

The second goal of this study was to determine the independent effects of speed and step length on required COF. The inter-dependence of speed and step length makes it difficult to separate and understand their independent effects. We hypothesized that increasing speed while holding step length constant would increase required COF. Our results showed that increasing speed while holding step length constant *decreased* required COF among older adults, and had no effect on required COF among young adults. As such, we rejected our hypothesis. We also hypothesized that increasing step length while holding speed constant would increase required COF. Our results showed that increasing step length while holding speed constant did indeed increase required COF. As such, we accepted our hypothesis.

The range of required COF values found here were similar to those reported in the literature.[4,5,7–10,20–22] Older adults exhibited a lower required COF compared to young adults during self-selected gait, which was similar to a previous study,[6] but differed from other studies that reported no differences in required COF between healthy older and young adults during self-selected gait.[7–9] Older adults also exhibited a lower required COF compared to young adults when gait speed was controlled, again differing from a previous study[4] that reported no differences between older and young adults during controlled slow, medium, and fast speeds without controlling step length. There are numerous possible reasons for these different findings between studies. In addition to self-selected gait speed and step lengths, other factors that differ between studies and that could influence the identification of age-related differences in required COF include footwear, experience or awareness of slipping,[22,23] and the experimental setup.

This study supports previous work indicating that older adults are not at increased risk of slipping,[4,7–9] as they did not exhibit a higher required COF compared to young adults.[4,7–94,7–9] In fact, a comparison of required COF between young and older adults without accounting for gait spatio-temporal characteristics indicated older adults had a lower required COF, which suggests a lower risk for slipping. Lockhart et al.[9] suggest that older adults are not at increased risk of slipping because they adopt a stable gait pattern with reduced speed and step length. Older adults do tend to adopt gait patterns with slower speeds and shorter step lengths than young adults,[12–14,16,18,24] and these adaptations have been associated with less severe slips when exposed to a slippery surface.[25] It has been suggested that these age differences may represent adaptations to provide a safer, more stable, gait pattern.[18] However, the current study suggests that older adults are not at increased risk of slipping even when walking with the same speed and step length as young adults.

Our results indicate speed and step length have independent and opposite effects on required COF. As speed was increased (while keeping step length constant), required COF tended to decrease among young adults, and decreased significantly among older adults. This can be seen by comparing the Slow-Constrained versus the Fast-Constrained gait conditions (Figure 3). On the other hand, as step length was increased (while keeping speed constant), required COF increased. This can be seen by comparing the Fast-Constrained versus the Fast gait conditions (Figure 3). The opposite effects of speed and step length on required COF are due to the differences in how strongly speed and step length affect shear and vertical GRFs at the same instant as the required COF, which are the numerator and denominator of required COF, respectively. Increasing speed and step length increased both shear and vertical GRFs. This is in agreement with previously reported relations between gait characteristics and GRFs.[26] Speed, however, had a larger relative effect on vertical GRF (denominator of required COF calculation) than shear GRF (numerator of required COF calculation) such that increasing speed *decreased* the required COF. For example, increasing speed from the Slow-Constrained condition to the Fast-Constrained condition (while keeping step length constant) resulted in a 29.1% increase in speed when averaged across young and older participants. This increase in speed increased shear GRF by 6.8%, increased vertical GRF by 13%, and decreased required COF by 6.1%. On the other hand, step length had a larger relative effect on shear GRF than vertical GRF such that increasing step length *increased* the required COF. For example, increasing step length from the Fast-Constrained condition to the Fast condition (while keeping speed constant) resulted in a 16.7% increase in step length when averaged across young and older participants. This increase in step length increased shear GRF by 34.3%, increased vertical GRF by 9.2%, and increased required COF by 24.4%. This quantitative example illustrates that step length has a stronger effect on required COF than speed. Speed and step length tend to be positively correlated if not controlled.[11] Increasing speed from the Slow condition to the Fast condition resulted in both a 29.1% increase in speed and a 17.3% increase in step length. Despite increasing a smaller percentage than speed, step length still had a larger effect on required

COF, as illustrated by the 14.3% increase in required COF rather than a decrease that might be expected if speed had a larger effect.

Several limitations of this study warrant mention. This study was limited to healthy, community-dwelling adults walking on a level surface in their own normal walking shoes, and the results may not generalize to other conditions or populations. It has been shown that sole hardness can affect peak required COF.[27] However, all participants in the current study wore similar soft-soled, closed-toe walking shoes, and we have no reason to believe that footwear systematically affected the results. This study also used real-time visual feedback in controlling gait speed, which could have had unintended effects on gait. However, because the data suggest speed and step length were well-controlled as intended, and because participants appeared to perform the task with little difficulty, it does not seem likely that the method of gait control had a significant impact on the results of this study.

In conclusion, age differences in required COF existed during self-selected gait, but these differences did not persist when experimentally-controlling speed and step length. These results support the need to account for these gait characteristics when trying to understand the underlying factors contributing to any age-related differences in required COF (or lack thereof). Speed and step length exhibited independent and opposite effects on required COF, with step length having a strong positive effect and speed a weaker negative effect. As such, the fact that older adults typically walk with both shorter step lengths and slower speeds has the net effect of decreasing the required COF. A practical implication of these results is that the risk of slipping increases with larger steps rather than increased speed, and a faster gait with short, quick steps would not increase required COF and the risk of slipping.

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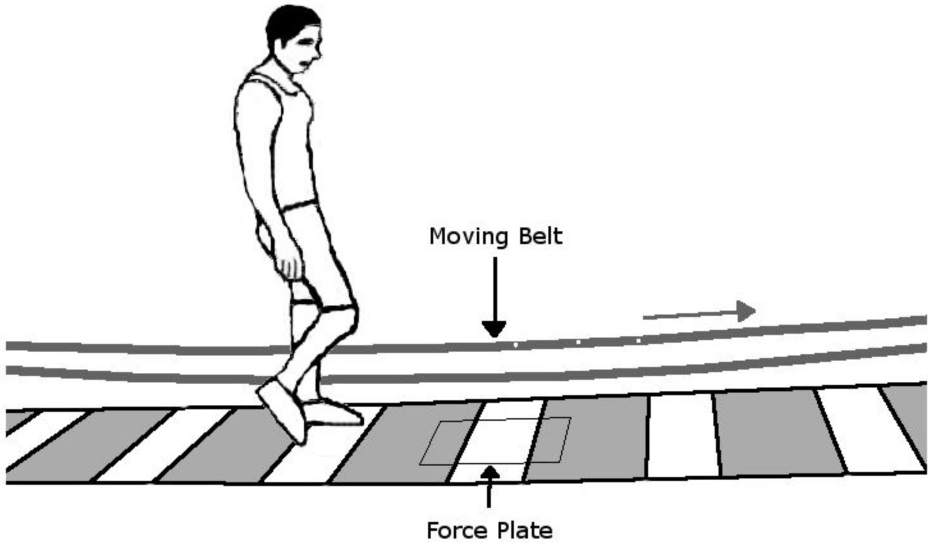

Figure 1.
Walkway setup for controlled gait trials. Speed was controlled by having participants match speed with a moving belt alongside the walkway. Step length was controlled by instructing the participants to step only on the white stripes across the walkway. In the cases where step length was not controlled, the stripes were removed from the walkway.

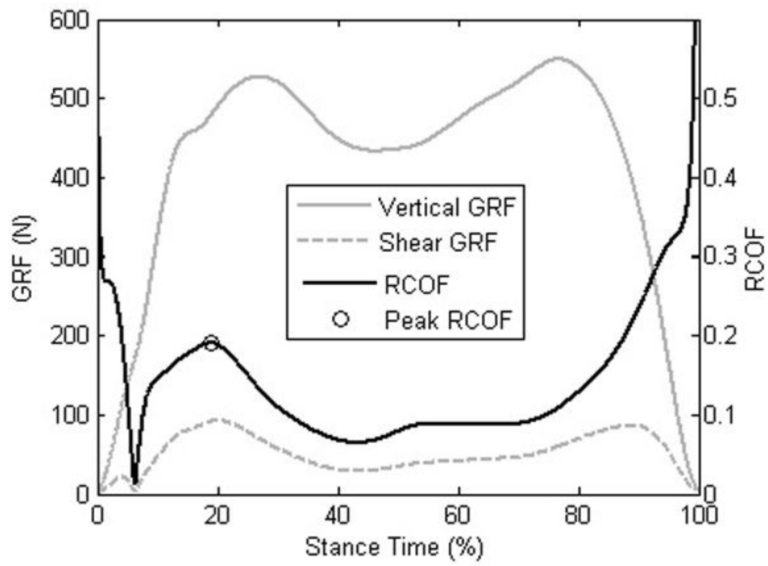

Figure 2.

Required COF was calculated throughout the stance phase as the ratio of the shear GRF to the vertical GRF. Peak required COF occurred at 10–20% stance phase, when the foot would tend to slip forward (i.e. when the resultant shear GRF opposed a forward slip). Note that the shear GRF shown here is the resultant of the anterior-posterior and medial-lateral components, and thus always positive.

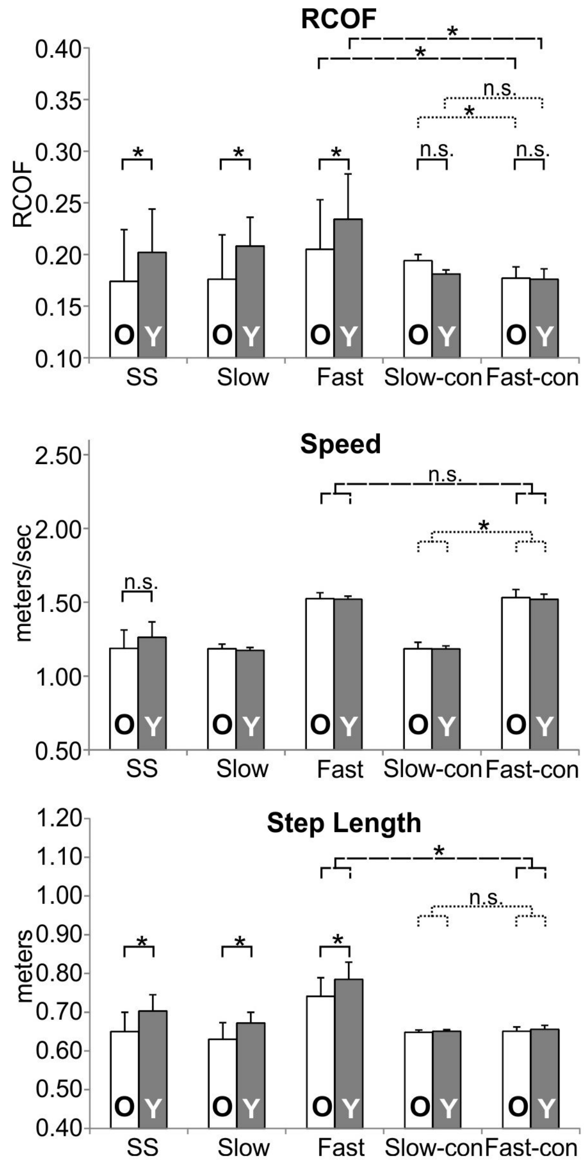

Figure 3.

Mean values of required COF, speed, and step length by age group for the five gait conditions tested. Solid brackets compared between age groups within each gait condition. Dotted brackets compared between Slow-Constrained and Fast-Constrained conditions to investigate the independent effect of speed on required COF. Dashed brackets compared between Fast and Fast-Constrained conditions to investigate the independent effect of step length on required COF. * = statistically significant ($p \leq 0.05$). n.s. = not statistically significant. O = Older group. Y = young group.