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BRIEF REPORTS

Investigating the Influence of Spatiotemporal Gait Characteristics on Shoe Wear Rate

Sarah C. Griffin, Sarah L. Hemler, and Kurt E. Beschorner

Department of Bioengineering, University of Pittsburgh, Pittsburgh, PA, USA

OCCUPATIONAL APPLICATIONS
We investigated the association between shoe wear rate and several metrics describing an individual's spatiotemporal gait characteristics (cadence, step length, and preferred walking speed). No associations were found, indicating that alternative metrics should be investigated to predict the individualized rate at which workers wear down shoe tread.

TECHNICAL ABSTRACT
Background: Shoe wear has been associated with increased slips and falls in the workplace. People wear down shoe tread at different rates; therefore, individualized shoe replacement timelines could improve resource targeting for organizations that use time as a basis for shoe replacement. Previous work has found that the shoe-floor kinetics, such as the friction requirements of walking, correlate with shoe wear rate. The use of easily measured metrics such as cadence, step length, or preferred walking speed to predict wear has not yet been investigated despite their relationship with friction requirements.
Purpose: This study seeks to determine the association between shoe wear rate and gait spatiotemporal characteristics.
Methods: Thirteen participants completed a longitudinal shoe wear study that consisted of a gait assessment followed by prolonged shoe wear in two pairs of slip-resistant shoes. The gait assessment was comprised of dry level-ground walking trials; kinematic and kinetic data were collected through optical motion capture and force plates. The participants' mean cadence, step length, and preferred walking speed were calculated. The participants then wore their shoes at work; the shoe wear rate was determined by measuring the periodic volumetric tread loss during this wear-at-work portion of the study.
Results: Three linear regression models found no significant association between the chosen gait metrics and the shoe wear rate.
Conclusions: The lack of an association between the spatiotemporal gait characteristics and shoe wear rate indicates that these factors may not explain the differences in wear rate between participants. This negative finding suggests that other measures such as the required coefficient of friction are better for individualizing footwear replacement guidelines.

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Slips, Trips, and Falls, Footgear, Biomechanics

1. Introduction

Falls on the same level are the second highest cause of non-fatal workplace injury and annually cost $10.8 billion in the United States (Liberty Mutual, 2020). These falls make up over 18% of all reported workplace injuries (Liberty Mutual, 2020). Furthermore, falls due to slips make up 40-50% of falls (Courtney et al., 2001), emphasizing that an increased understanding of the causes of slips and methods for prevention are needed.

The condition of shoe tread is an important factor in mitigating slips and falls. A study by Verma et al. (2014) found that workers using shoes worn for less time (<6 months) had a lower rate of slipping than those using older (>6 months) shoes. Additionally, increased wear on a shoe makes the floor feel more slippery (Chiou et al., 1996) and causes the traction performance of the heel to decrease (Beschorner et al., 2020; Grönqvist, 1995; Hemler et al., 2019; Hemler et al., 2020; Sundaram et al., 2020). One study (Hemler et al., 2020) found that cumulative walking distances of ∼210 km led to substantive reductions in the shoe-floor available coefficient of friction (ACOF). However, different individuals wear through their shoes at different rates (Hemler et al., 2021) indicating that the shoe wear rate is dependent on participant-specific factors.

CONTACT Sarah C. Griffin SCG57@pitt.edu Department of Bioengineering, University of Pittsburgh, Pittsburgh, PA, USA

One participant-specific factor relevant to shoe wear is the required coefficient of friction (RCOF). RCOF is the minimum coefficient of friction needed between the floor and the shoe for an individual to walk without slipping (Chang et al., 2011) and is dependent on gait kinetics (Kim et al., 2005). Hemler et al. (2021) found that higher RCOF and peak shear forces, but not normal forces, were associated with an increased shoe wear rate. No other gait metrics have been compared with the shoe wear rate.

RCOF has been positively correlated with the step length and negatively correlated with cadence (Anderson et al., 2014). Other gait kinematics such as the heel contact velocity and whole-body translational acceleration have also been found to be related to the RCOF (Lockhart et al., 2003). Furthermore, several studies have indicated that a decrease in RCOF among older adults relative to younger adults may be related to changes in step length and preferred walking speed (Anderson et al., 2014; Kim et al., 2005; Yamaguchi & Masani, 2019). No studies have yet investigated the impact of spatiotemporal gait characteristics (e.g., cadence, step length, and preferred walking speed) on shoe wear rate. Therefore, as RCOF is associated with wear rate (Hemler et al., 2021), these same spatiotemporal characteristics that are related to RCOF may also be associated with wear rate. If so, the ability to easily measure cadence, step length, and preferred walking speed in the workplace may enable development of individualized shoe replacement guidelines.

Currently, some companies provide tread gauges for individuals to test their shoes (ShoesForCrews, 2019), based on the presumed relationship between tread depth and ACOF (Li & Chen, 2005; Li et al., 2006). Additionally, Beschorner et al. (2020) recommended comparing the size of the continuous worn region on the shoe outsole to the size of a AA or AAA battery to determine if worn shoes should be replaced. These methods capitalize on monitoring shoe wear to detect the need for shoe replacements. However, predicting wear utilizing spatiotemporal gait characteristics could be advantageous in organization-level planning to determine when shoes should be replaced to reduce slip and fall risk. Therefore, this study sought to determine the association between shoe wear rate and gait spatiotemporal characteristics (cadence, step length, and preferred walking speed). Due to the associations between RCOF and these characteristics, we hypothesized that increased wear rate would be associated with decreased cadence, increased step length, and increased preferred walking speed.

2. Methods

This study consisted of two sections. In the first section, kinetic and kinematic gait data were collected to determine individual gait metrics. In the second wear-at-work section, participants were given shoes to wear in their normal work environment for a natural wear process. The gait metrics measured in the lab were then compared to the individual-specific shoe wear in the workplace. This current report is a secondary analysis of data presented earlier by Hemler et al. (2021).

2.1. Participants

Thirteen healthy participants from a recruited pool of 23 were analyzed (10 male, 3 female; mean (standard deviation): age: 41.6 (13.0) years; height: 1.75 (0.10) m; mass: 89.3 (12.3) kg; shoe size: 9.5 (2.6) US Men). Certain self-reported inclusion requirements were utilized: participants were required to regularly wear treaded shoes, spend more than 75% of walking time on manufactured surfaces, and to stand or walk for at least four hours in a typical day. Exclusion criteria included any neurological problems, musculoskeletal injury in the previous two years, musculoskeletal disorders, osteoporosis, or arthritis. Each participant was provided with two pairs of shoes; only right shoes that were worn for 100 km were included in this analysis and participants were not included if they did not properly contact the force plates with both feet during the gait assessment. Proper contact was defined as the entire foot landing on the force plate for the duration of the stance phase of walking. These criteria resulted in the analysis of 21 right shoes across the 13 participants. There were four reasons that the shoes from the original 23 participants were not included in this analysis: the participant withdrew from the study prior to completing one month of walking in the shoes ($n = 11$ shoes); the participant walked fewer than 100 km during the study due to low activity ($n = 8$ shoes); the participant reported discomfort when wearing the shoes ($n = 4$ shoes); or the participant did not properly contact both force plates during the gait assessment ($n = 2$ shoes). Participants worked across a variety of industries including trade, transportation, and utilities ($n = 1$ participant), manufacturing ($n = 5$ participants), leisure and hospitality ($n = 5$ participants), and education and health services ($n = 2$ participants). Written informed consent was obtained at the start of the study according to the University of Pittsburgh Institutional Review Board. This research was performed in accordance with the Declaration of Helsinki of 1975.

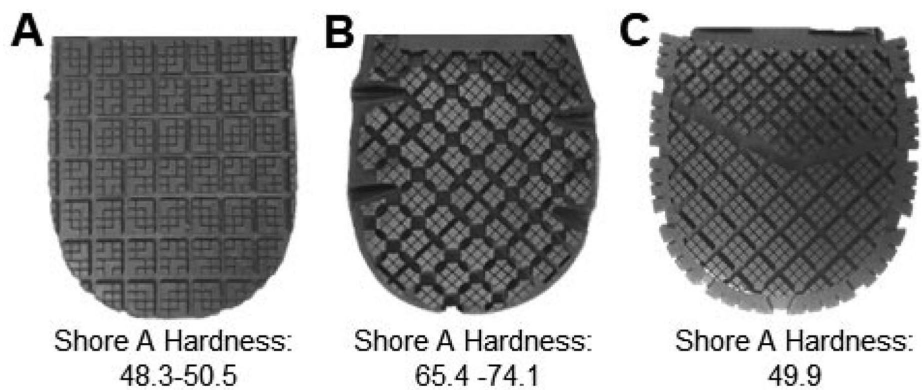

Figure 1. Images of the shoe tread patterns adapted from Hemler et al. (2021). Shoe A consisted of SRB 1977 (shoe), SRM 4750 (boot) or SRM 225 (boot) for men and SRB 972 (shoe) or SRM 2550 for women. For shoe B, both men and women wore the Blast Bouffee 159961 (shoe) or Dawson160004 (boot) produced by safeTstep. Finally, shoe C was the Rowan 77280 (boot) for men and August 77319 (boot) for the women. All soles were made of a rubber compound.

2.2. Experimental Protocol

Prior to data collection, participants were provided with two pairs of slip-resistant footwear, classified as shoe A, B, and C based on their brand and associated tread design. Each shoe type was offered in a boot or shoe form, depending on the individual's occupational requirements. Participants received shoe A and either shoe B or shoe C (Figure 1).

Participants were asked to perform a series of dry, over-ground walking trials while wearing each of the two pairs of shoes provided, at a pace resembling how they walk in the workplace. Optical motion capture data was collected using reflective markers (Vicon 10 T40S cameras, Oxford, UK) at 120 Hz. There were 10 markers on the foot and ankle. In this study, the reflective marker of interest was the heel marker placed at the posterior-most point of the shoe, about 30 mm superior to the ground. Kinetic data was synchronously collected using two force plates (Bertec 4060 A, Columbus, OH) at 1080 Hz. Up to 10 walking trials with proper force plate contacts on both feet were completed for each of the shoe types.

Following the gait assessment, participants were asked to wear the provided shoes in their workplace, alternating pairs each month so tread wear could be measured in the lab during months where the shoes were not worn by the participants. A pedometer, validated by Hunter et al. (2017) was attached to the right shoe of each pair to track the distance walked per month (MilestonePod, Milestone Sports, Columbia, MD). After each month of wear, the tread volume loss was measured using negative shoe heel molds. The tread in the molds were filled with water at baseline and after the month where the participants first walked a total of at least 100 km. The change in mass of the water between these measurements was determined and converted to tread volume loss (Hemler et al., 2021; Moghaddam et al., 2019). Wear rate was calculated as the ratio of tread volume loss to distance walked (based on the pedometer) at the first month in which the 100 km threshold was reached.

2.3. Data and Statistical Analysis

Step time was the time difference between the right foot contacting the first force plate and the left foot contacting the second force plate of the subsequent step. A threshold of 25 N was used to identify foot contact. Cadence was the reciprocal of the step time. Step length was the distance between the right heel marker and the left heel marker in the direction of walking progression at each foot's respective contact time. Preferred walking speed was the ratio of step length to step time. Means of these metrics were obtained across all trials in which the participant had proper force plate contacts for both feet.

Three linear regression analyses were conducted with wear rate as the dependent variable. In each model, one of the spatiotemporal gait characteristics was a between-participant factor and the shoe type was included as a within-participant factor. The effects of the covariate, shoe type, are not described further because this effect has been previously reported (Hemler et al., 2021). Separate statistical analyses were performed because of the covariation across the independent variables. A significance level of $\alpha = 0.05$ was used for all analyses.

3. Results

The mean (SD) number of trials per participant included in the analysis was 9.5 (1.0) and ranged from

Table 1. Descriptive statistics for each metric with units in parentheses.

Metric	Mean	SD
Wear Rate (mm^3/km)	7.70	4.83
Cadence (steps/s)	1.83	0.19
Step Length (m)	0.76	0.06
Preferred Walking Speed (m/s)	1.39	0.20

6 to 10 trials. Descriptive statistics for each metric are provided in Table 1. Participants wore the shoes for 1.6 (0.9) months before reaching the 100 km threshold. All associations were non-significant: 1) between cadence and wear rate (Figure 2A; $F_{1,17}$=1.7, p = 0.208); 2) between step length and wear rate (Figure 2B; $F_{1,17}$=0.6, p = 0.450); and 3) between preferred walking speed and wear rate (Figure 2C; $F_{1,17}$=1.7 p = 0.204).

4. Discussion

We investigated the associations between spatiotemporal gait characteristics and shoe wear rate. The hypotheses that a lower cadence, longer step length, and increased preferred walking speed would be associated with an increased wear rate were not supported. These results suggest that spatiotemporal gait characteristics may not be well correlated with shoe wear rate, despite their previously reported mutual association with RCOF.

The mean values found here for the cadence, step length, and preferred walking speed are similar to those in other studies (Kim et al., 2005; Lockhart et al., 2003). A supplemental statistical analysis found no significant association (range of p-values: 0.052-0.367) between each of the spatiotemporal gait characteristics (cadence, step length, and preferred walking speed) and the RCOF. This non-significant result was unexpected since other studies found associations between these factors and RCOF (Kim et al., 2005; Yamaguchi & Masani, 2019). One potential explanation is that the relationship between RCOF and spatiotemporal factors may not be as strong in the non-older adult population. Several studies (Anderson et al., 2014; Kim et al., 2005; Yamaguchi & Masani, 2019) investigated differences in the gait metrics within the context of aging and found a stronger relationship between RCOF and these spatiotemporal factors. However, we only included young to middle aged participants. Previous research has shown that heel contact velocity, whole body translational acceleration (Lockhart et al., 2003), and angle of the center of pressure relative to the center of mass (Yamaguchi et al., 2013) may affect RCOF. Therefore, future studies may investigate the impact of these factors on

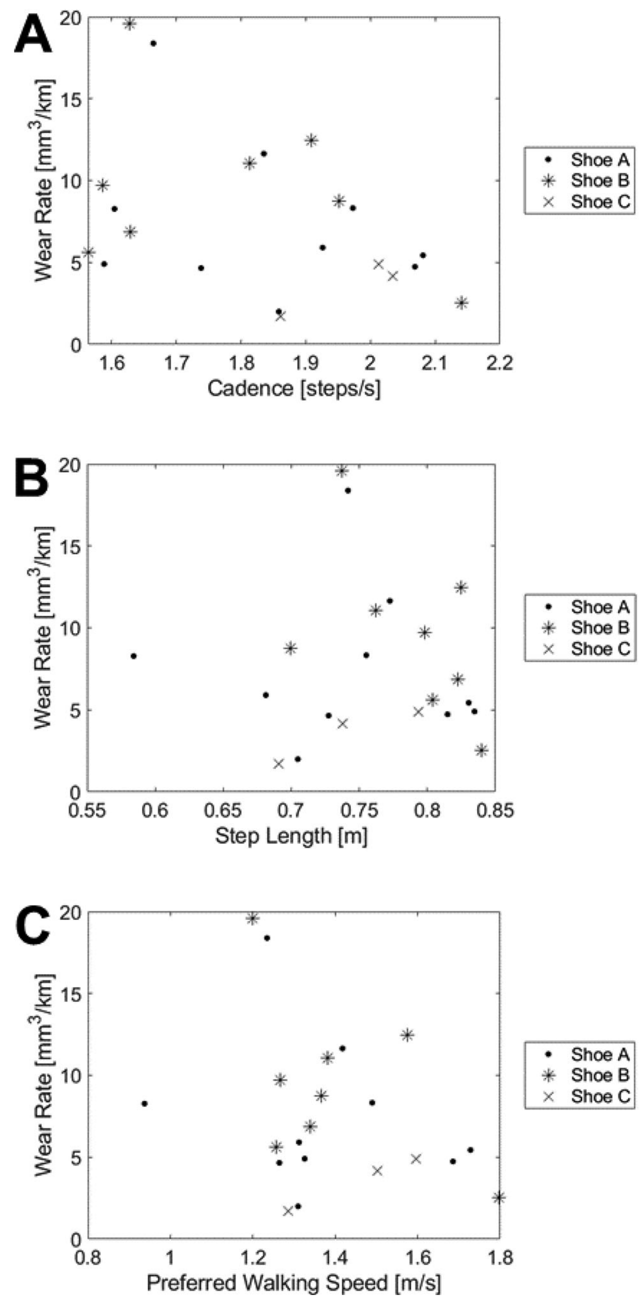

Figure 2. Wear rate plotted against A) cadence, B) step length, and C) preferred walking speed. Marker types represent shoe type.

wear rate. The lack of association between the spatiotemporal gait characteristics investigated in this study and the RCOF may explain the lack of association between these gait characteristics and wear rate.

There are a few limitations that should be mentioned. Kinetic and kinematic data were collected in a laboratory setting, and the shoes were worn in the participants' workplaces. It is possible that the gait mechanics of the participants varied in the laboratory space compared to their workplaces. For example, walking surfaces have been shown to affect individuals' gait spatiotemporal characteristics (Menant et al., 2009; Thies et al., 2005). This finding indicates that individuals' working conditions likely affected their spatiotemporal characteristics and the data from the controlled setting may not be as representative. Further, the study only examined the participants' movements during straight, level walking. In the workplace, the participants perform different activities that could have altered wear. The use of wearable technology to evaluate gait and other activities in the work environment may provide better predictions of shoe wear; a greater understanding of the specific gait requirements of the individual participants would allow this variable to be controlled. Additionally, the variety of industries, job tasks, and working environments present in the study could have increased variability and reduced the study's ability to identify an effect. We do not expect strong gender differences because the wear rate is not dependent on body weight (Hemler et al., 2021), and prior research has not indicated sex or gender differences in the RCOF at moderate walking speeds (Burnfield & Powers, 2003). Yet, there may be other aspects of sex that influence the relationship between spatiotemporal gait parameters and the wear rate. Therefore, the over-representation of male participants could have had an unexplained impact on the results. Additional research with more equal representation of male and female participants may address these issues. Finally, shoe wear rate may not be linear, and repeated measurements of wear may better capture these relationships as shoes approach the need to be replaced.

In summary, this study demonstrated that the wear rate of a shoe may not be associated with an individual's cadence, step length, or preferred walking speed. Walking kinetics, rather than kinematics, may be a better indication of shoe wear rate. More advanced metrics that identify gait kinetics may be needed to predict the frequency at which employees require footwear replacement.

Conflict of Interest

The authors declare no conflict of interest.

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ORCID

Sarah C. Griffin http://orcid.org/0000-0002-1937-6652
Sarah L. Hemler http://orcid.org/0000-0002-0436-5256
Kurt E. Beschorner http://orcid.org/0000-0002-3058-2617

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