Published in final edited form as:
Gait Posture. 2021 May ; 86: 157–161. doi:10.1016/j.gaitpost.2021.03.006.

GAIT KINETICS IMPACT SHOE TREAD WEAR RATE

Sarah L Hemler[a], **Jessica R. Sider**[a], **Mark S. Redfern**[a], **Kurt E. Beschorner**[a]

[a]Department of Bioengineering, University of Pittsburgh, 301 Schenley Place, 4420 Bayard Street, Pittsburgh, PA, USA 15213

Abstract

Background: Adequate footwear is an important factor for reducing the risk of slipping; as shoe outsoles wear down, friction decreases, and slip and fall risk increases. Wear theory suggests that gait kinetics may influence rate of tread wear.

Research question: Do the kinetics of walking (i.e., the shoe-floor force interactions) affect wear rate?

Methods: Fourteen participants completed dry walking trials during which ground reaction forces were recorded across different types of shoes. The peak normal force, shear force, and required coefficient of friction (RCOF) were calculated. Participants then wore alternating pairs of shoes in the workplace each month for up to 24 months. A pedometer was used to track the distance each pair of shoes was worn and tread loss was measured. The wear rate was calculated as the volumetric tread loss divided by the distance walked in the shoes. Three, mixed linear regression models were used to assess the impact of peak normal force, shear force, and RCOF on wear rate.

Results: Wear rate was positively associated with peak RCOF and with peak shear force, but was not significantly related to peak normal forces.

Significance: The finding that shear forces and particularly the peak RCOF are related to wear suggests that a person's gait characteristics can influence wear. Therefore, individual gait kinetics may be used to predict wear rate based on the fatigue failure shoe wear mechanism.

Keywords

RCOF; gait kinetics; shoe wear; slips and falls; fatigue failure

---

Corresponding author: Sarah L. Hemler slh148@pitt.edu.

Conflict of interest statement
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

1. Background

Slips and falls are a major cause of injury that can cause severe health loss (James et al., 2020). In the United States, 18% of non-fatal occupational injuries occur every year due to same-level falls with a Worker's Compensation financial burden of $10.6 billion (Liberty Mutual Research Institute for Safety, 2017). Additionally, over 5 million hospitalizations occur annually as a result of falling in the non-elderly population (National Center for Injury Prevention and Control, 2018). Slipping has been found to contribute to 40–62% of occupational fall-related injuries (Courtney, Sorock, Manning, Collins, & Holbein-Jenny, 2001; Manning, Ayers, Jones, Bruce, & Cohen, 1988). Thus, there is a need to improve slip and fall prevention strategies.

Slips resulting in falls are caused by a lack of friction between the flooring and footwear. Previous research has shown that increased required coefficient of friction (RCOF) and/or decreased available coefficient of friction (ACOF) are associated with a higher risk of slipping (Beschorner, Albert, & Redfern, 2016; Burnfield & Powers, 2006; Hanson, Redfern, & Mazumdar, 1999). The RCOF is the ratio of shear to normal forces during walking and varies depending upon walking speed and other characteristics of gait (Kim, Lockhart, & Yoon, 2005). The ACOF is the measured friction capability of a shoe-floor-contaminant interface. Footwear design has been shown to be a modifiable factor that influences the ACOF and slipping (Bell, Collins, & Chiou, 2018; Iraqi, Vidic, Redfern, & Beschorner, 2020; Jones, Iraqi, & Beschorner, 2018; Verma et al., 2011; Verma et al., 2014).

Slip-resistant shoes, which are designed for enhanced friction, typically have small tread blocks separated by tread channels. When the shoe contacts a fluid-covered floor surface, these tread blocks disperse the fluid out of the shoe-floor interface to reduce under-shoe fluid pressures (Hemler, Charbonneau, et al., 2019), therefore decreasing the risk of slipping (Beschorner, Albert, Chambers, & Redfern, 2014; V.H. Sundaram et al., 2020). However, as shoe tread wears down, under-shoe fluid dispersion capability decreases and slip risk increases (Beschorner et al., 2014; Hemler, Charbonneau, et al., 2019; Vani H Sundaram et al., 2020). Furthermore, research has shown that in the workplace, shoes worn for more than six months present a higher risk of slipping than those worn less than six months (Verma et al., 2014). While tread wear has emerged as an important feature influencing ACOF and slip risk, the factors influencing the rate at which shoes become worn remains largely unknown. As such, there is a paucity of research examining factors influencing the mechanisms and rate of shoe tread wear.

Multiple potential mechanisms may explain the impact of kinetics on shoe wear (Sato et al., 2020). Given that the shoe outsole is typically manufactured from elastomeric material, elastomeric wear theory is relevant to shoes. Elastomeric wear has been analyzed in a plethora of applications including bearing seals and tires (Békési, 2012; Békési & Váradi, 2010; Békési, Váradi, & Felhős, 2011; Lupker, Cheli, Braghin, Gelosa, & Keckman, 2004); two common theories to explain elastomeric wear include fatigue failure (Mars & Fatemi, 2002, 2004) and Archard's wear, which is an empirical relationship that is intended to capture multiple modes of wear (e.g., abrasive, fretting) (Archard, 1953). Fatigue failure can occur when elastomers experience cyclic loading (Mars & Fatemi, 2004). Under purely compressive loads, cracks in the material are unlikely to form as no tensile stress is present (Mars & Fatemi, 2002) (Figure 1, stage 1). As the compressive load is accompanied by a shear load (Figure 1 – stage 2), the material encounters tensile stresses leading to crack nucleation and growth (Mars & Fatemi, 2002). Further increasing shear forces leads to increased tensile forces and potential crack propagation. Normal compressive forces and shear forces interact to form directions of principal tensile stress, which are likely to cause more crack nucleation and growth, (Figure 1, stage 3) eventually leading to fatigue failure that causes the material to dislodge from the shoe. Thus, shear and normal forces applied to an elastomeric material are key in determining fracture lines and therefore wear profiles.

In gait analysis, shear and normal forces, along with the ratio of the shear to normal forces (RCOF) are commonly used to describe the interaction at the shoe-floor interface (Beschorner et al., 2016; Chang, Chang, & Matz, 2011). As shear forces increase, especially relative to the normal force (increases in RCOF), the principal tensile stress of the shoe outsole elastomer concurrently increases, leading to the potential for material failure and the formation of wear particles (Mars & Fatemi, 2004). As such, fatigue failure applied to gait indicates that increased shear forces and subsequent RCOF may lead to increased elastomeric tread wear. Archard's wear has also been used to understand elastomer wear; this theory states that the volumetric wear of a material is proportional to the sliding distance and the applied normal force while inversely proportional to the material hardness (Archard, 1953). Archard's wear suggests that increased normal force during gait leads to increased volumetric tread wear. Thus, ground reaction force parameters that are commonly measured in gait analysis are potentially relevant to shoe tread wear.

In summary, shoe wear is an important risk factor relevant to slipping; wear theory suggests that gait kinetics (in particular, normal forces, shear forces, and RCOF) may contribute to shoe wear, yet there is a lack of empirical evidence linking gait kinetics to wear rate. Thus, the purpose of this study is to understand the effects of gait kinetics on the rate of shoe tread wear.

2. Methods

2.1 Summary

This research consisted of a longitudinal study comprised of a gait assessment and wearing shoes in the workplace (Figure 2). Two pairs of SR shoes were fitted to each participant. Gait kinetics and kinematics were collected during dry, over-ground walking in each pair of shoes. Participants then wore the shoes in the workplace alternating between pairs each month. At baseline and during the off-month of wear, tread geometry was captured using negative molds of the heel of the shoes to determine the volumetric tread loss and subsequent wear rate based on the distance walked by the participants. The change in ACOF and under-shoe fluid pressures was also tracked and reported (Beschorner et al., 2020; Hemler, Pliner, Redfern, Haight, & Beschorner, 2020).

2.2 Participants

Fourteen healthy participants (11 male and 3 female; age: 42 ± 13 yrs.; height: 176 ± 11 cm; mass: 90 ± 13 kg; shoe size 9.6 ± 2.3 US Men's Sizing) from a recruited cohort of 23 recruited participants were analyzed. Inclusion criteria included participants who regularly wore treaded shoes, spent more than 75% of walking time on manmade surfaces, and were on their feet for at least 4 hours in a typical day. Exclusion criteria included any neurological problems, musculoskeletal history in the previous 2 years, musculoskeletal disorders, neurological problems, osteoporosis, or arthritis. Included participants worked in the following industries on primarily indoor flooring surfaces: trade, transportation & utilities, manufacturing, leisure and hospitality, and education and health services. Only right shoes that were worn for 100 km were included in this analysis (excluding 23 pairs of shoes leading to 23 pairs of shoes included in the study) since preliminary observations revealed that this was the minimum amount of use where a reliably measurable amount of wear could be observed. There were three reasons that shoes were excluded from analysis: the participant discontinued wearing the shoe because they reported discomfort while wearing the shoes at work (n_{shoes} = 4), the participant withdrew from the study prior to completing one month of walking in the shoes (n_{shoes} = 11), and the participant walked fewer than 100 km total in the enrollment period due to low activity levels (n_{shoes} = 8). Written informed consent was obtained at the start of the study according to the University of Pittsburgh Institutional Review Board and the research has been conducted in accordance with the principles of the Declaration of Helsinki.

2.3 Experiment Protocol

Participants were provided with two pairs of footwear – shoe A and: shoe B or shoe C (Figure 3). Within each shoe type, boots or shoes with the same tread pattern were provided depending on their occupational requirements (Table 1). As shoe B was discontinued from manufacturing during the study, four participants received shoe C rather than shoe B. All participants were asked to complete a series of dry, over-ground walking trials in a biomechanics lab at a pace resembling their gait while in their workplace. While wearing each pair of the given shoes and reflective markers to track motion, participants walked over two force plates (Bertec 4060A, Columbus, OH) which collected normal and shear forces at 1080 Hz. The gait assessment concluded when ten good force plate hits were recorded for the right foot for each shoe type. Peak normal forces and shear forces prior to flat foot during stance phase were recorded (Figure 4). The peak RCOF was calculated based on a 100N normal force threshold, positive longitudinal shear component, and during the first 200 ms of stance phase (Chang et et al., 2011). This corresponded to the maximum between the 3rd and 4th peak characterized by Perkins (Perkins, 1978). The right shoe of each pair was fitted with a pedometer to track the distance walked (MilestonePod, Milestone Sports, Columbia, MD), (Hunter, Miller, & Suydam, 2017). Shoes were then shipped to participants to wear in their workplace for one month at a time.

At baseline and after each month of wear, the tread wear of the shoes was measured. A rectangular mold (92 mm x 76 mm x 28 mm) of each shoe heel was made using a silicone rubber compound (Smooth-On Inc.; Macungie, PA; Oomoo® 25) at an angle of 17° as in previous experiments (Hemler, Charbonneau, et al., 2019; Hemler et al., 2020). The right foot molds for the baseline level and the first month of wear that surpassed the 100 km threshold were used to determine the volumetric tread loss during wear in the workplace. Each mold was placed on a scale (MicroMall™ 300g/0.001g B3003T) and the inverse tread blocks were filled with water using a pipette. The mass of the water required to fill the molds was measured three times. The molds were allowed to dry between measurements. The change in the water mass between the baseline level and threshold-passing mold was calculated, converted to volume, and normalized to the cumulative distance that the shoes were worn. This metric was termed the wear rate [mm^3/km].

2.4 Statistical Analysis

Four, mixed linear regression models were used in this study to assess the impact of gait kinetics and shoe design on wear rate. Specifically, the first model consisted of testing the effect of peak normal force (between subject) and shoe type (within subject) on wear rate (dependent variable). The second model assessed the effect of peak shear force (between subject) and shoe type (within subject) on wear rate (dependent variable). The third model tested the effect of peak RCOF (between group) and shoe type (within group) on wear rate (dependent variable). Lastly, the fourth model assessed the impact of outsole Shore A hardness (independent) on wear rate (dependent) across subjects. For all models, wear rate was logarithmic-transformed to normalize residuals and satisfy the linearity assumption.

3. Results

Participants walked a cumulative distance of 167 ± 69 km (range: 101–351 km) until the time when wear volume was determined (i.e., end of the first month when shoe usage exceeded the 100 km threshold) which occurred after 1.9 ± 1.4 months (range: 1–7 months). Within those months, participants walked 100 ± 80 km per month. The standard deviation between the three volume measurements of each mold was 54 mm^3, on average (the standard deviation ranged from 6–125 mm^3). The cumulative volumetric tread wear ranged from 324–3450 mm^3 (baseline to the 100 km threshold month) across the shoes.

Across all shoes and participants, peak normal force ranged from 816 to 1270 N, peak shear force ranged from 87 to 235 N, and peak RCOF ranged from 0.090 to 0.23 (Table 2). The geometric mean of the wear rate was 6.7 mm^3/km with a range from 1.7 to 20.0 mm^3/km, and a mean 95% confidence interval of 5.1–8.9 mm^3/km. Overall, Shoe A had the largest range for the wear rate, peak normal force, peak shear force, and peak RCOF. Shoe C had the smallest range for the wear rate, peak normal force, and peak shear force, and lowest average values across all four variables while Shoe B had the highest average values across the four variables.

In the first model (Akaike Information Criterion corrected: AICc = 63.2), peak normal force ($F_{1,12}$=.01, p=0.924) and shoe type ($F_{2,9}$=3.8, p=0.063) were not associated with wear rate (Figure 5). In the second model, (AICc = 56.4), the peak shear force was positively associated with wear rate ($F_{1,14}$=5.4, p=0.037), but there was no association between wear rate and the shoe type ($F_{2,9}$=2.7, p=0.118). In the third model (AICc = 42.6), peak RCOF ($F_{1,14}$=6.6, p=0.023) was positively associated with wear rate, and shoe type ($F_{2,11}$=2.9 p=0.100) was not. Furthermore, in the third model, increases in RCOF of 0.01 and 0.1 were associated with 6.8% and 93.0% increased wear rate, respectively. The fourth model showed that wear rate was not affected by the shoe outsole hardness ($F_{1,11}$=0.6, p = 0.472).

4. Discussion

In this study, the peak shear forces and peak RCOF, but not the peak normal force nor shoe outsole hardness, were associated with the wear rate. The peak RCOF model showed that increases of 0.1 in the RCOF were associated with nearly doubling of the predicted wear rate. As such, the service life of shoes (use before requiring replacement) is highly dependent on that individual's gait kinetics, specifically the shear force and its ratio to the normal force (RCOF).

This research builds off previous literature which has shown that gait parameters are related to slip risk (Beschorner et al., 2016; Hanson et al., 1999; Iraqi, Cham, Redfern, Vidic, & Beschorner, 2018). Previous research has shown that RCOF during dry locomotion is predictive of slip risk (Beschorner et al., 2016), and thus a reasonable gait metric to study for assessing slip risk. This study identifies a second pathway in which RCOF could increase slip risk. Increased wear rate (associated with higher RCOF) will lead to faster growth of a worn region. The amount of shoe outsole wear, measured by the size of the worn region, is associated with decreased ACOF, increased under-shoe fluid pressures, and increased slip risk (Hemler, Charbonneau, et al., 2019; Hemler, Sundaram, & Beschorner, 2019; V.H. Sundaram et al., 2020).

These results are consistent with the fatigue failure wear theory as a mechanism for shoe outsole elastomeric wear. Tearing energy, also known as the strain energy release rate, has been shown to contribute to elastomer fatigue and subsequent failure (De & White, 2001; Mars & Fatemi, 2002). Furthermore, an advantage of applying this fatigue failure wear theory lies in the geometry-independent determination of using fatigue life as a characteristic of elastomer (De & White, 2001). These findings on fatigue failure are applicable for shoe outsole wear regardless of tread design. However, designs to reinforce material properties in the directions of principle shear for a given tread design could potentially influence wear rate. These principle shear directions are determined by the characteristics of locomotion. Archard's wear equation, however, relies on normal force and shoe outsole hardness for predicting wear. This study shows that neither normal force nor hardness influenced shoe wear rate, supporting the use of fatigue failure wear theory as a relevant basis for predicting shoe outsole elastomeric wear.

There are a few limitations from the study that should be acknowledged. The participants wore shoes on primarily indoor surfaces. As surface roughness has a strong influence on wear, these results may not generalize to outdoor wear (Sato et al., 2020). Furthermore, the specific material composition may affect the wear rate of the shoes which could lead to the slight changes in wear rates between shoe brands (Sato et al., 2020). Participants worked in a variety of fields possibly introducing gait variability among participants to perform different movements across work environments. Further studies with a greater degree of control over the workplace conditions may be helpful for confirming the results of this study. However, the clear trend in the data is seen even with this variability, supporting the robustness of the results to assess natural wear in the general workplace.

Gait kinetics impact shoe wear rate. The results are consistent with an elastomer fatigue failure model of shoe wear. Although this work focused on slip-resistant shoes, the theoretical approach and conclusions are valid for both slip-resistant and non-slip-resistant shoes. Furthermore, this research suggests that a person’s gait has an impact on wear which influences shoe traction performance. By measuring and analyzing simple gait kinetics (peak shear force or peak RCOF), individual shoe replacement recommendations could be made to improve shoe safety.

5. Conclusion

Overall, this research identifies individual peak shear forces and peak RCOF as predictors of shoe wear rate, which may also provide insight into a fatigue failure as the mechanism dominating the wear of shoe outsoles. In this study, peak shear forces and peak RCOF, a measure of peak shear forces relative to normal forces during dry walking, were found to be associated with tread wear rate. This work supports fatigue failure as a mechanism of shoe tread wear for normal gait. Therefore, this understanding of gait kinetics and the wear mechanism may inform the need for individualized shoe replacement recommendations to prevent injury caused by the decline in traction performance of worn shoes.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

This study was funded by grants from the National Institute for Occupational Safety & Health (NIOSH R01 OH 010940), the National Science Foundation (NSF GRFP 1747452), and the National Institute of Arthritis and Musculoskeletal and Skin Diseases (R43AR064111). The authors would like to acknowledge the lab manager of the Human Movement and Balance Laboratory, Jenna Trout, and the students on the project who contributed to data collection through testing the shoes and coordinating with the participants: Ellen Martin, Bridget Moyer, Johanna Siegel, Vani Sundaram, Claire Tushak, & Paul Walter.

6. References

Archard J. (1953). Contact and rubbing of flat surfaces. Journal of applied physics, 24(8), 981–988.

Békési N. (2012). Modelling Friction and abrasive wear of elastomers. Advanced Elastomers-Technology, Properties and Applications. Retrieved from https://books.google.com/books?hl=en&lr=&id=nOecDwAAQBAJ&oi=fnd&pg=PA341&dq=Modelling+friction+and+abrasive+wear+of+elastomers&ots=1EianqlYdN&sig=9v2bikAvbXKSyhaP-9C8sIz1REA#v=onepage&q=Modelling%20friction%20and%20abrasive%20wear%20of%20elastomers&f=false

Békési N, & Váradi K. (2010). Wear simulation of a reciprocating seal by global remeshing. Periodica Polytechnica. Engineering. Mechanical Engineering, 54(2), 71.

Békési N, Váradi K, & Felhős D. (2011). Wear simulation of a reciprocating seal. Journal of Tribology, 133(3).

Bell JL, Collins JW, & Chiou S. (2018). Effectiveness of a no-cost-to-workers, slip-resistant footwear program for reducing slipping-related injuries in food service workers: a cluster randomized trial. Scandinavian Journal of Work, Environment & Health.

Beschorner KE, Albert DL, Chambers AJ, & Redfern MS (2014). Fluid pressures at the shoe– floor–contaminant interface during slips: Effects of tread & implications on slip severity. Journal of Biomechanics, 47(2), 458–463. [PubMed: 24267270]

Beschorner KE, Albert DL, & Redfern MS (2016). Required coefficient of friction during level walking is predictive of slipping. Gait & posture, 48, 256–260. [PubMed: 27367937]

Beschorner KE, Siegel JL, Hemler SL, Sundaram VH, Chanda A, Iraqi A, … Redfern MS. (2020). An observational ergonomic tool for assessing the worn condition of slip-resistant shoes. Applied ergonomics, 88, 103140. [PubMed: 32678768]

Burnfield JM, & Powers CM (2006). Prediction of slips: an evaluation of utilized coefficient of friction and available slip resistance. Ergonomics, 49(10), 982–995. [PubMed: 16803728]

Chang W-R, Chang C-C, & Matz S. (2011). The effect of transverse shear force on the required coefficient of friction for level walking. Human factors, 53(5), 461–473. [PubMed: 22046720]

Courtney TK, Sorock GS, Manning DP, Collins JW, & Holbein-Jenny MA (2001). Occupational slip, trip, and fall-related injuries–can the contribution of slipperiness be isolated? Ergonomics, 44(13), 1118–1137. [PubMed: 11794761]

De SK, & White JR (2001). Rubber technologist's handbook (Vol. 1): iSmithers Rapra Publishing.

Hanson JP, Redfern MS, & Mazumdar M. (1999). Predicting slips and falls considering required and available friction. Ergonomics, 42(12), 1619–1633. [PubMed: 10643404]

Hemler SL, Charbonneau DN, Iraqi A, Redfern MS, Haight JM, Moyer BE, & Beschorner KE (2019). Changes in under-shoe traction and fluid drainage for progressively worn shoe tread. Applied ergonomics, 80, 35–42. [PubMed: 31280808]

Hemler SL, Pliner EM, Redfern MS, Haight JM, & Beschorner KE (2020). Traction performance across the life of slip-resistant footwear: preliminary results from a longitudinal study. Journal of Safety Research.

Hemler SL, Sundaram VH, & Beschorner KE (2019). Influence of slip-resistant shoe classification and shoe age on under-shoe hydrodynamics during human slips. Paper presented at the International Society of Biomechanics & American Society of Biomechanics, Calgary, Alberta, Canada.

Hunter JG, Miller RH, & Suydam S. (2017). Accuracy of a shoe-worn device to measure running mechanics.

Iraqi A, Cham R, Redfern MS, Vidic NS, & Beschorner KE (2018). Kinematics and kinetics of the shoe during human slips. Journal of Biomechanics, 74, 57–63. [PubMed: 29759653]

Iraqi A, Vidic NS, Redfern MS, & Beschorner KE (2020). Prediction of coefficient of friction based on footwear outsole features. Applied ergonomics, 82, 102963. [PubMed: 31580996]

James SL, Lucchesi LR, Bisignano C, Castle CD, Dingels ZV, Fox JT, … Liu Z. (2020). The global burden of falls: global, regional and national estimates of morbidity and mortality from the Global Burden of Disease Study 2017. Injury prevention.

Jones TG, Iraqi A, & Beschorner KE (2018). Performance testing of work shoes labeled as slip resistant. Applied ergonomics, 68, 304–312. [PubMed: 29409649]

Kim S, Lockhart T, & Yoon H-Y (2005). Relationship between age-related gait adaptations and required coefficient of friction. Safety Science, 43(7), 425–436. [PubMed: 20582254]

Liberty Mutual Research Institute for Safety. (2017). 2017 Liberty Mutual Workplace Safety Index. Retrieved from https://www.libertymutualgroup.com/about-liberty-mutual-site/news-site/Pages/2017-Liberty-Mutual-Workplace-Safety-Index.aspx

Lupker H, Cheli F, Braghin F, Gelosa E, & Keckman A. (2004). Numerical prediction of car tire wear. Tire Science and Technology, 32(3), 164–186.

Manning DP, Ayers I, Jones C, Bruce M, & Cohen K. (1988). The incidence of underfoot accidents during 1985 in a working population of 10,000 Merseyside people. Journal of Occupational Accidents, 10(2), 121–130.

Mars WV, & Fatemi A. (2002). A literature survey on fatigue analysis approaches for rubber. International Journal of fatigue, 24(9), 949–961.

Mars WV, & Fatemi A. (2004). Factors that affect the fatigue life of rubber: a literature survey. Rubber Chemistry and Technology, 77(3), 391–412.

National Center for Injury Prevention and Control, C. (2018). 10 Leading Causes of Nonfatal Emergency Department Visits, United States. Retrieved from https://webappa.cdc.gov/sasweb/ncipc/nfilead.html

Perkins PJ (1978). Measurement of slip between the shoe and ground during walking. In Walkway surfaces: Measurement of slip resistance: ASTM International.

Sato S, Yamaguchi T, Shibata K, Nishi T, Moriyasu K, Harano K, & Hokkirigawa K. (2020). Dry sliding friction and Wear behavior of thermoplastic polyurethane against abrasive paper. Biotribology, 100130.

Sundaram VH, Hemler SL, Chanda A, Haight JM, Redfern MS, & Beschorner KE (2020). Worn Region Size of Shoe Outsole Impacts Human Slips: Testing a Mechanistic Model. Journal of Biomechanics, 105(109797).

Sundaram VH, Hemler SL, Chanda A, Haight JM, Redfern MS, & Beschorner KE (2020). Worn Region Size of Shoe Outsole Impacts Human Slips: Testing a Mechanistic Model. Journal of Biomechanics, 109797. [PubMed: 32423543]

Verma SK, Chang WR, Courtney TK, Lombardi DA, Huang Y-H, Brennan MJ, … Perry MJ. (2011). A prospective study of floor surface, shoes, floor cleaning and slipping in US limited-service restaurant workers. Occupational and environmental medicine, 68(4), 279–285. [PubMed: 20935283]

Verma SK, Zhao Z, Courtney TK, Chang W-R, Lombardi DA, Huang Y-H, … Perry MJ. (2014). Duration of slip-resistant shoe usage and the rate of slipping in limited-service restaurants: results from a prospective and crossover study. Ergonomics, 57(12), 1919–1926. [PubMed: 25205136]

Highlights:

- A knowledge gap exists regarding the impact of gait kinetics on shoe outsole wear.
- Gait kinetics were measured for 14 participants wearing different types of shoes.
- Shear forces and the RCOF during gait positively influenced shoe tread wear rate.
- The findings support fatigue failure as a wear mechanism for shoe tread.
- Individual gait kinetics may be useful to recommend wear thresholds and footwear.

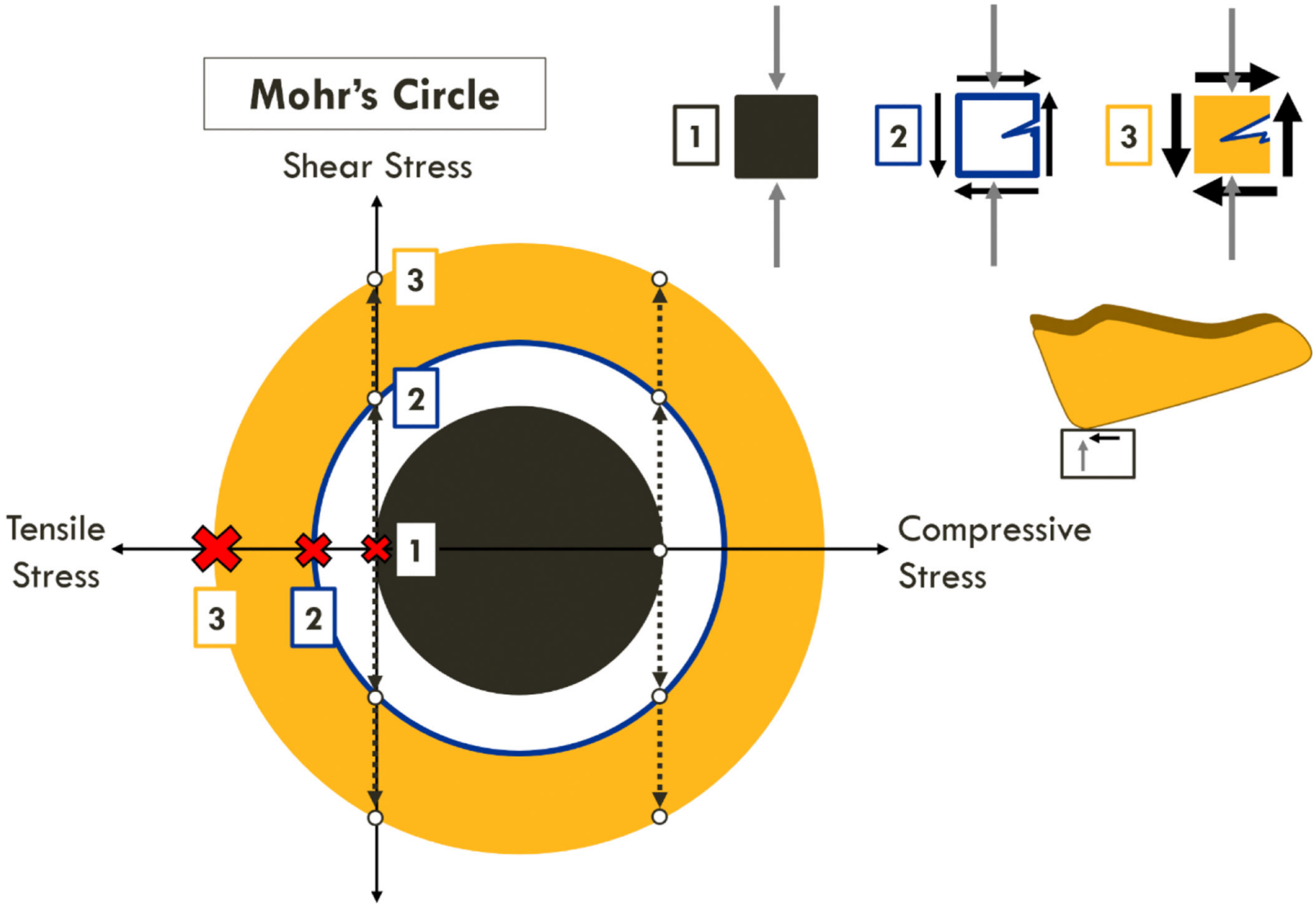

Figure 1.

Diagram of fatigue failure elastomeric wear theory. At stage 1 (black block and small black circle on the shear stress diagram), the block experiences uniaxial compressive (normal) loading. There is zero tensile stress in this scenario. At stage 2 (hollow, thick blue/black-outlined block and circle), shear stresses are added to the block with the same normal stress. The shear stress causes an increase in the principal tensile stress (shown by the small red 'x' above indicator '2'). At stage 3 (yellow/gray block and large yellow/gray circle), shear stress magnitudes are increased with the same normal load; shear stress increases on the diagram and likewise, the tensile stress on the horizontal axis also increases. The kinetics during gait heel strike are represented with the shear force in black and normal force in gray (middle right side of figure).

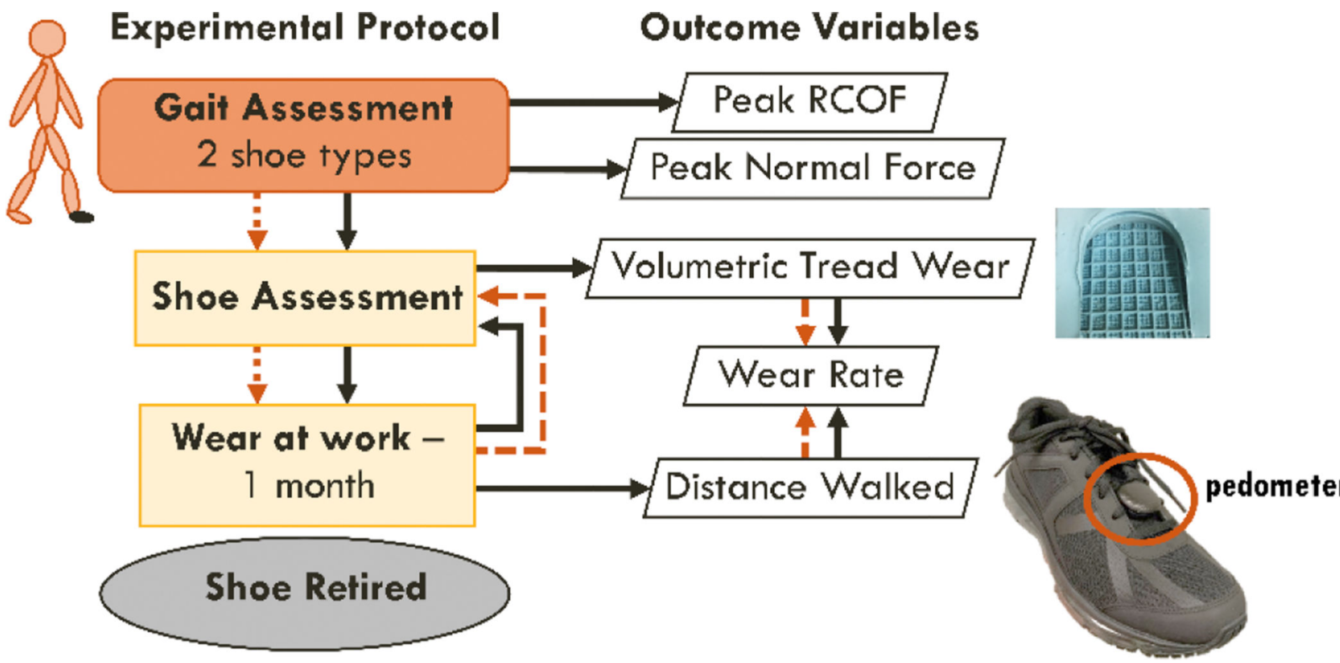

Figure 2.
Flowchart of experimental protocol.

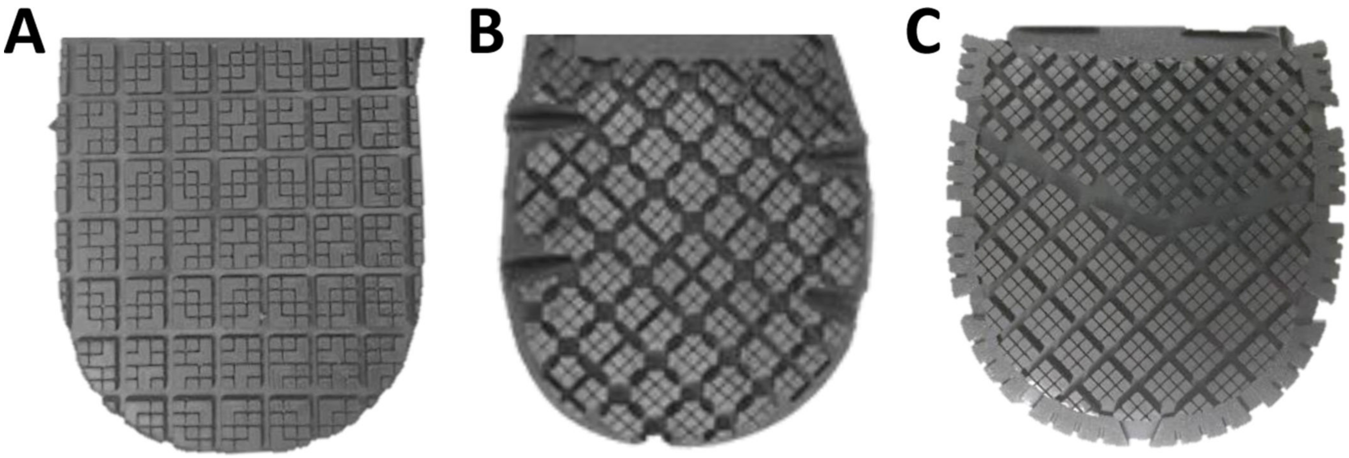

Figure 3.
Representations of the three tread types for A) shoe A, B) shoe B, and C) shoe C.

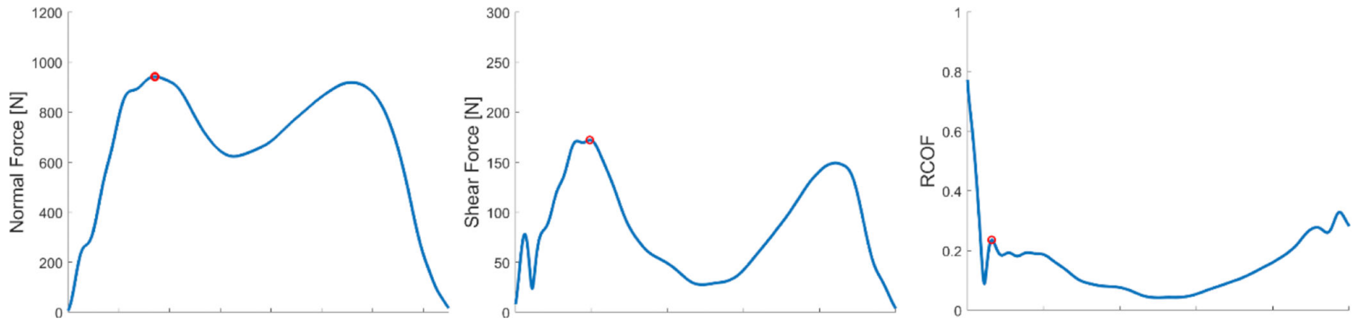

Figure 4.

Representative kinetic data during stance phase for the A) normal force, B) shear force, and C) RCOF. Peak measurements for each plot are signified with a red circle.

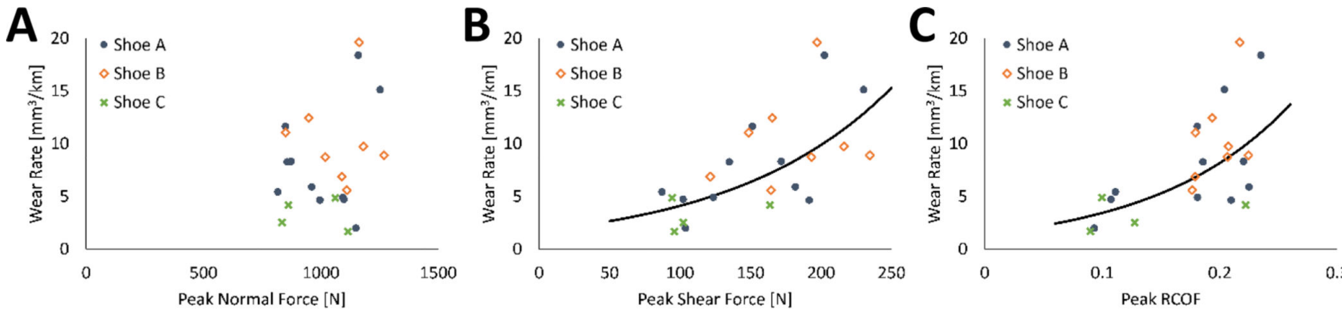

Figure 5.

Wear rate with respect to A) peak normal force, B) peak shear force, and C) peak RCOF for the three shoe types. The regression line is shown in black according to the natural logarithmic transformation for the peak shear force ($wear\ rate\ = 2.2 * e^{\frac{0.0066}{N} * \ Shear\ Force}$) and peak RCOF ($wear\ rate = 1.92 * e^{6.58 * RCOF}$).

Table 1:

List of footwear code, brand, model, and short-term hardness for each men's and women's footwear option. Two footwear options were used for Shoe A – Boot as the first model was discontinued during the recruitment phase.

Shoe Type	Shoe/Boot Option	Footwear Brand	Men's Model	Women's Model	Short Term Hardness (Shore A)
A	Shoe	SRMax	SRB1977	SRB972	48.3
	Boot	SRMax	[1]SRM4750/[2]SRM225	SRM2550	[1]50.5/[2]48.5
B	Shoe	safeTstep	Blast Bouffee 159961	Blast Bouffee 159961	65.4
	Boot	safeTstep	Dawson 160004	-	74.1
C	Boot	ShoesForCrews	Rowan 77280	August 77319	49.9

Table 2:

Participant information (n, Age, Mass, Height, BMI) and kinetic results (normal force, shear force, RCOF), and wear rate grouped by shoe type. Mean (standard deviation) is listed with the range in italics. Geometric mean is listed for wear rate.

Shoe Type	Number of Shoes	Age	Mass [kg]	Height	BMI	Peak Normal Force [N]	Peak Shear Force [N]	Peak RCOF	Wear Rate [mm^3/km]	Wear Rate 95% CI [mm^3/km]
A	11	41 (11) *25–55*	89.5 (12.3) *71.1–106*	174.5 (9.8) *162.5–192*	29.3 (3.2) *25.0–34.9*	1009 (150) *816–1252*	153 (46) *87–230*	0.18 (0.05) *0.09–0.24*	6.8 (5.0) *2.0–18.4*	*4.76–11.5*
B	8	41 (14) *24–58*	95.1 (12.7) *76.8–110.2*	182.1 (10.3) *169.5–198*	28.7 (3.2) *24.0–34.0*	1079 (135) *850–1270*	180 (37) *121–235*	0.20 (0.02) *0.18–0.22*	9.7 (4.3) *5.6–19.6*	*6.8–14.0*
C	4	45 (14) *25–55*	83.7 (13.3) *71.1–95.6*	170.1 (5.4) *164.5–177.5*	28.9 (4.7) *25.0–34.9*	968 (141) *833–1115*	114 (33) *94–164*	0.13 (0.06) *0.09–0.22*	3.1 (1.5) *1.7–4.9*	*1.0–5.7*