Published in final edited form as:
Appl Ergon. 2020 January ; 82: 102959. doi:10.1016/j.apergo.2019.102959.

Influence of Averaging Time-Interval on Shoe-Floor-Contaminant Available Coefficient of Friction Measurements

Kurt E. Beschorner[a,*], **Arian Iraqi**[a], **Mark S. Redfern**[a], **Brian E. Moyer**[b,c], **Rakié Cham**[a,d,e]

[a]Department of Bioengineering, University of Pittsburgh, Benedum Engineering Hall #302, 3700 O'Hara St., Pittsburgh, PA 15261, United States

[b]Crossroads Consulting, LLC, 1334 Luzerne St Ext, Johnstown, PA 15905

[c]Mechanical Engineering, University of Pittsburgh Johnstown, Johnstown, PA 15905

[d]Department of Physical Therapy, University of Pittsburgh

[e]Department of Ophthalmology, University of Pittsburgh

Abstract

Available coefficient of friction (ACOF) is a common metric of footwear traction performance. ACOF is the ratio of friction to normal force, often averaged over a time-interval. The time-interval needed to achieve repeatable and valid ACOF is unknown. A post-hoc analysis was performed on nine shoe-floor-contaminant combinations to assess the repeatability and bias of data averaged across 4 time-intervals (2 ms, 50 ms, 100 ms, 200 ms) after the target normal force was reached. The ability to predict human slips was assessed for ACOF across these intervals. Differences in repeatability and validity across the four intervals were small. However, statistically significant differences were observed for the shortest compared with the longest interval (lower repeatability yet modestly improved predictive ability). Given the limited impact of time-interval on the results, a shorter interval of 50 ms is recommended to enable testing of smaller floor samples.

Introduction

Falling accidents initiated by slipping events are a major public safety concern. Falls account for 26% of non-fatal occupational injuries (U.S. Department of Labor-Bureau of Labor Statistics, 2018). Slipping is a common initiating event of falls in occupational settings (Courtney et al., 2001).

Footwear and flooring properties are widely recognized to influence shoe-floor friction (Blanchette and Powers, 2015a; Iraqi et al., 2018a; Jones et al., 2018; Moghaddam and Beschorner, 2016; Yamaguchi et al., 2015; Yamaguchi et al., 2017). The traction

*Corresponding author: Kurt E. Beschorner, PhD, 306 Schenley Place, 4420 Bayard Street, Pittsburgh, PA 15213, beschorn@pitt.edu.

performance of footwear and flooring designs is commonly quantified by the available coefficient of friction (ACOF) using a tribometer (Beschorner et al., 2007; Chang et al., 2001a; Iraqi et al., 2018a; Jones et al., 2018; Wilson, 1990; Yamaguchi et al., 2015; Yamaguchi et al., 2017). The ACOF is calculated from the time-series ratio ($F_F(t)/ F_N(t)$) of friction force ($F_F(t)$) and the normal force ($F_N(t)$). The probability of experiencing a slip can be predicted using the difference between ACOF and an individual's required coefficient of friction (RCOF) (Burnfield and Powers, 2006; Hanson et al., 1999; Iraqi et al., 2018a). The RCOF is typically calculated from ground reaction forces during unperturbed walking (Beschorner et al., 2016; Chang et al., 2011; Hanson et al., 1999).

An important consideration for calculating the ACOF is the selection of the force ration time-series. Timing considerations may be important since previous research has identified potential time-dependent behavior of friction (described in the subsequent paragraph). The timing of ACOF measurements can be parameterized into 1) the duration of the time-interval used for the calculation of ACOF; and 2) the time relative to heel contact when the measurements begin (Figure 1). The influence of the time relative to heel contact has been the subject of previous investigation (Chang et al., 2001a; Grönqvist et al., 2003; Strandberg, 1985) yet little effort has been focused on the impact of the time-interval duration on the measured ACOF. The time-interval varies from a single sample (Blanchette and Powers, 2015b; Wilson, 1996) to hundreds of ms (Beschorner et al., 2007; Grönqvist et al., 1989; Iraqi et al., 2018a; Yamaguchi et al., 2015). Currently, little evidence is available to guide the best practice for estimating the ACOF. The beginning of the force ratio time-series used to estimate the ACOF is typically when the normal force and/or sliding speed reach a specified level, defined by the particular test method (Beschorner et al., 2007; Blanchette and Powers, 2015b; Cowap et al., 2015; Grönqvist et al., 1989; Iraqi et al., 2018a; Jones et al., 2018; Wilson, 1996; Yamaguchi et al., 2015; Yamaguchi et al., 2017) (Figure 1, dotted line). This study focuses on the time-interval duration of force ratio data used for calculating the ACOF.

Averaging time-series data over a time-interval can improve repeatability but limit the types of flooring that can be tested. Time-series force data and the subsequent force ratio data fluctuate throughout a trial (Beschorner et al., 2007; Grönqvist et al., 2003; Grönqvist et al., 1989). These fluctuations can be due to variations in topography across a floor surface (Chang, 2002; Widas, 2013), the stick-slip phenomenon (Chang et al., 2001b; Jones et al., 2017; Moore, 1972), or time-dependent mechanics (squeeze-film or viscoelastic deformation of the shoe material) (Beschorner et al., 2014; Chang et al., 2001b; Grönqvist et al., 2003; Grönqvist et al., 1989; Strandberg, 1985). Averaging the force ratio data over time combines the peaks and valleys in these fluctuations. A longer interval may improve the repeatability of the measurement by reducing the impact of these fluctuations. However, longer time-intervals have drawbacks that can negatively impact the applicability of the tests. For example, longer tests may be incapable of testing shorter floor samples. Thus, identifying the shortest averaging interval that also yields repeatable results is desirable.

The biomechanical justification for the selection of a particular averaging interval is unclear. Slipping events happen quickly. Typically, the heel starts sliding forward about 30–50 ms after heel contact and then reaches its maximum sliding velocity within 200 ms of heel contact (Iraqi et al., 2018b). Thus, averaging intervals in the range of 0 ms (representing the instant of slip-start) to 200 ms could be reasonable. Within this range of biomechanically-appropriate time-intervals, further research is needed regarding the effect of time-interval duration on the resulting measurements.

The goal of this study is to evaluate the repeatability, bias, and validity of shoe-floor-contaminant ACOF values using different force ratio averaging intervals. Validity of the different averaging intervals is assessed based on the ability of the calculated ACOF values to predict human slips.

2. Methods

This study represents a secondary analysis of a data set that has been presented by Iraqi et al (2018a). In the previous study, force ratio data for 9 shoe-floor contaminant conditions were recorded and combined with RCOF values to predict the slip outcomes of 124 human slips (based on 89 participants). The shoe-floor-contaminant conditions were selected because human slip data were available for these conditions. The present study reanalyzes the force ratio time-series data using different averaging intervals to assess the impact of the averaging interval on ACOF repeatability and validity in predicting slip events. As such, the methodological approach will only be briefly described in this current study.

2.1. Review of previous study

In the previous study (Iraqi et al., 2018a), data from multiple studies, where human participants were exposed to slippery contaminants, were pooled. For all of these studies, ethics approval was received from the University of Pittsburgh Internal Review Board and all participants provided informed consent prior to participation. The participants were young and healthy. Participants donned a harness and reflective markers. Participants completed at least 3 baseline trials on dry ground before being unexpectedly exposed to a slippery liquid contaminant. Many of the participants then changed to a different pair of footwear, performed at least 15 baseline walking trials to allow them to return to baseline gait, and then were exposed to a second liquid contaminant. Data from the second exposure was not included if the participant experienced a slip during the first exposure or if they showed other signs of anticipation as described in Beschorner et al. (2019).

Ground reaction forces were analyzed to determine the RCOF values from unperturbed gait data. Kinematic data were analyzed to determine slip outcomes (i.e., occurrence of slipping). RCOF was averaged across multiple baseline gait trials preceding the exposure to the contaminant. The RCOF was extracted based on the ratio of friction to vertical force consistent with previously described methods (Beschorner et al., 2016; Chang et al., 2011; Iraqi et al., 2018a). The slip outcome (slip and no slip) was based on whether the heel slipping distance exceeded 30 mm (Iraqi et al., 2018a; Iraqi et al., 2018b; Jones et al., 2018; Leamon and Son, 1989). Heel slipping distance was defined as the displacement between slip-start and end-of-slip. The timing of slip-start and end-of-slip were defined based on local minima in the heel slipping speed.

Nine footwear designs and one flooring (vinyl composite tile flooring, Armstrong Earthstone ®) were included. High viscosity contaminants were utilized including diluted glycerol (50% to 90% glycerol; 50 to 10% water) and canola oil (see supplementary table for detailed information of the contaminants used). For these studies, the contaminant was typically selected to achieve moderately slippery condition to enable differentiation in the proportion of slip events across footwear.

The Portable Slip Simulator tribometer (Aschan et al., 2005; Iraqi et al., 2018a; Jones et al., 2018; Moghaddam and Beschorner, 2016) was used to quantify ACOF of the shoe-floor-contaminant combinations. This device contains electromagnetic linear motors that apply a vertical force and horizontal sliding motion. A force plate beneath the floor surface records ground reaction forces at 1080 Hz. The device was operated in the prior study using different vertical forces, sliding speeds and shoe angles. Given that the best slip predictions were observed for the test conditions, 250 N (± 25 N) normal force, 17° shoe angle, and 0.5 m/s sliding speed (Iraqi et al., 2018a) and that these methods are prescribed in a draft testing standard (ANSI/NFSI, 2019), force data from these test methods were considered in the present study. Loading rate was not specifically controlled in this study but had a mean (standard deviation) of 2200 (500) N/s. Data were collected over three sessions for each shoe-floor-contaminant condition with five trials in each session. Between each session, the footwear and flooring were removed from the device, cleaned and reattached to the device. The force ratio time-series were calculated as the ratio of the resultant friction force to the normal force after the normal force first exceeded 250 N (Figure 2).

2.2. Data Analysis Methods

The ACOF values were calculated over four time-intervals: 2 ms (2 data points), 50 ms, 100 ms, and 200 ms. All of the averaging intervals started at the first datum when the normal force reached the target force (250 N).

2.2.1. Repeatability and bias across averaging intervals—Repeatability will be presented in two ways: within-session repeatability recorded within the same testing session and between-session repeatability. Between-session repeatability reflects the variation inherent in setting up the device and preparing the test materials.

ANOVA methods were used to assess within-session and between-session repeatability. To test within-session repeatability, the variance was calculated across the trial replicates for each session and footwear-contaminant combination. An ANOVA was used to test the impact of footwear type, session, and averaging interval on the transformed within-session variance. To test between-session repeatability, the variance was calculated across the three sessions for each footwear and each of the four averaging intervals. This variance was the dependent variable and footwear type and averaging interval were the independent variables. The between-session repeatability data set lacked the degrees of freedom to include interaction effects and so only main effects were included in these models. A log transformation was applied to within-session and between-session variance values to achieve normally-distributed residual values. Post-hoc Tukey HSD analyses were performed to make comparisons across footwear designs and across testing sessions (for the within-session repeatability analysis). If a significant time-interval effect was observed, Dunnett's test was used to compare the three shorter time-interval conditions relative to the 200 ms interval condition. Standard deviation values across footwear designs were combined and reported as root mean square error for each averaging interval.

Bias was examined by performing an ANOVA with the mean ACOF values across session and repetitions as the dependent variable and the following independent variables: shoe, averaging interval, and their interaction. If averaging interval was significant, this would indicate a bias across the different averaging time-intervals. In this case, a Dunnett's test was performed to determine the testing conditions that deviated from the existing method (200 ms). The interaction term was included to determine if differential bias existed across the footwear designs.

2.2.2. Validity analysis—The validity of each of the averaging intervals was assessed by developing logistic regression models with ACOF-RCOF as the regressor and slip outcome of each trial as the dependent variable. A separate model was developed for each time-interval. Receiver operating characteristic (ROC) curves were developed to map sensitivity and specificity of the model. For each of the intervals, the ROC curves were compared using a χ^2 test (Beschorner et al., 2019). Specifically, the three shorter intervals (2, 50, 100 ms) were compared relative to the longer time-interval (i.e., current practice, 200 ms, Bonferroni correction: 0.05/3 = 0.017).

3. Results

The root mean square (RMS) of the within-session variance ranged from 0.0011 to 0.0022. The within-session variance was influenced by the footwear condition ($F_{8,94} = 3.7$, $p = 0.001$) and by the averaging interval ($F_{3,94} = 19.1$, $p<0.001$) (Figure 3A). The within-session variance did not systematically differ across the three sessions ($F_{2,94} = 1.2$, $p = 0.32$). On average, the within-session variance was approximately 0.001 higher for the 2 ms interval than the other intervals. The within-session variance (Figure 3A) was low compared to the between-session variance (Figure 3B) and compared to typical ACOF values (Figure 4). The between-session repeatability had an RMS error of between 0.0086 and 0.0088 and did not significantly differ across averaging intervals ($F_{3,24} = 0.2$, $p =0.884$) (Figure 3B). The between-session repeatability varied across footwear types ($F_{8,24} = 7.3$, $p <0.001$). In particular, S3 had greater between-session repeatability than B2, S4, S5, and S2NT and S1, B3 and B1 had greater between-session repeatability than S2NT (see supplementary table for more information on shoe codes).

The ACOF was influenced by the averaging interval ($F_{3,504} = 3.1$, $p=0.026$) (Figure 4). The mean ACOF values for the 2 ms interval were approximately 0.002 lower than the other averaging intervals (Figure 4, "Combined"). No interaction effect between interval and footwear was observed ($F_{24,\ 504} = 1.5$; $p = 0.060$).

A shorter averaging interval was associated with small improvements in slip predictions. The logistic regression fit models (Figure 5A) were nearly identical across the four time intervals. The 200 ms time-interval method was associated with an area under the ROC of 0.815. The area under the curve was 0.819, 0.823 and 0.830 for the 100 ms, 50 ms and 2 ms time-interval methods, respectively (Table 1). The only one of these methods with an ROC curve that reached significance relative to the existing averaging method was 2 ms ($\chi^2_{(1)}$ = 7.6, p=0.006), which achieved a small improvement in area under the curve (0.015) (Figure 5B).

4. Discussion

Reducing the averaging interval had a small impact on the repeatability, bias, and validity of the test methods. While these changes were statistically significant, the effect sizes were small. The small effects indicate that ACOF was not sensitive to the time-interval duration. In particular, using an averaging interval of 50 ms led to no significant changes in repeatability, no significant bias, and no significant change in the prediction of slips. Furthermore, by reducing the averaging interval from 200 ms to 50 ms, the testing distance required is reduced by 75 mm (given a 0.5 m/s testing speed). Thus, the averaging interval of 50 ms offers an important advantage without any notable disadvantage.

The results are somewhat consistent with previous research. For example, the time-ACOF relationship has shown that longer contact times led to slightly larger ACOF values on average (Grönqvist et al., 2003; Grönqvist et al., 1989). Furthermore, that study found that the results stabilized as the slide time continued to increase. The present study found that the shortest time-interval (2 ms) had slightly lower ACOF values than the 3 longer time-intervals and a stabilization of values was observed for averaging intervals of 50 ms and longer. The interval where this stabilization occurred was smaller in this study (50 ms) than the previous research (250 ms) (Grönqvist et al., 2003). However, Gronqvist et al. referenced their contact times from heel contact as opposed to the time when the normal force reached steady-state. Thus, these differences in stabilization times may be explained through methodological differences.

An important contribution of this study is that it quantifies the repeatability of the device. The within-session repeatability was very small (<0.005) and the between-session repeatability was below 0.01 (a common resolution for ACOF reports (ASTM, 2019)). However, the between-session repeatability was as high as 0.013 for some shoes. This upper-limit of variability should be considered by operators when interpreting data with this device.

Utilizing a shorter testing distance has important practical implications regarding the types of surfaces that can be tested. Given that 150 ms relative to heel contact is commonly required to achieve the force (Figure 2), which is then maintained for 200 ms, approximately 350 ms is needed to complete the test (ANSI/NFSI, 2019). Thus, the shoe typically travels 175 mm during a test. Assuming that 50 mm of the shoe is in contact during a test (Jones et al., 2018; Singh and Beschorner, 2014), the test requires approximately 225 mm of a consistent flooring surface to complete a test. Standard testing floor samples come in lengths of 300 mm (ASTM, 2016) and 150 mm (ASTM, 2019; SATRA Technology, 2019). Using an averaging interval of 50 ms reduces the total uninterrupted floor distance to approximately 150 mm. Thus, reducing the averaging interval to 50 ms can enable the test to be applied to all of the current standard flooring.

Considerations beyond the scope of this study may be important when selecting the averaging interval. As mentioned previously, a major implication of the time-interval is the size of the floor sample that can be tested. Another consideration could be surfaces or tribometers where stick-slip occurs. In these cases, using a time-interval long enough to include multiple periods of this variation should be considered. These other considerations should be prioritized when selecting the time-interval.

Some limitations of the study should be acknowledged. While all of the tests built up normal force within 200 ms of heel contact, the force buildup rate was not precisely controlled. Thus, the tests did not reflect the total contact time but rather the time after the force reached the target force. Further inquiry into the interaction between heel contact time and the time-interval duration may be warranted. Furthermore, the study only considered a single flooring and expanding this study to a wider variety of floorings may yield new insights. Lastly, the results of this study may not necessarily apply when substantial slip-stick is observed as can happen with non-oily contaminant conditions (Jones et al., 2018).

In conclusion, this study demonstrated that the averaging interval and subsequently the testing distance specified in the ANSI/NFSI B101.7 test method can be substantially shortened with minimal influence on bias, repeatability, or validity for predicting slips (ANSI/NFSI, 2019). This will enable the test method to be applicable to more flooring surfaces. Thus, it is recommended that test methods incorporate a shorter time-interval of 50 ms.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

This study was funded by the National Institute on Aging (NIA R44 AR064111), the National Institute for Occupational Safety and Health (R01 OH007592, R01 OH 008986 and R01 OH 010940), by the National Center for Research Resources (S10 RR027102), and by Saf-Gard Safety Shoe Company ® (Grant #0049178).

6. References

ANSI/NFSI, 2019 Draft: ANSI NFSI B101.7: Standard Test Method for Lab Measurement of Footwear Heel Outsole Material Slip Resistance on Liquid-Contaminated Floor Surfaces. The National Floor Safety Institute, Southlake, TX.

Aschan C, Hirvonen M, Mannelin T, E., R., 2005 Development and validation of a novel portable slip simulator. Applied Ergonomics 36, 585–593. [PubMed: 15970203]

ASTM, 2016 ASTM F2508–16e1: Standard Practice for Validation, Calibration, and Certification of Walkway Tribometers Using Reference Surfaces. ASTM International, West Conshohocken, PA.

ASTM, 2019 ASTM F2913–19: Standard Test Method for Measuring the Coefficient of Friction for Evaluation of Slip Performance of Footwear and Test Surfaces/Flooring Using a Whole Shoe Tester. ASTM International, West Conshohocken, PA.

Beschorner KE, Albert DA, Chambers AJ, Redfern MR, 2014 Fluid Pressures at the Shoe-Floor-Contaminant Interface During Slips: Effects of Tread & Implications on Slip Severity. Journal of Biomechanics 47, 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, Iraqi A, Redfern MS, Cham R, Li Y, 2019 Predicting slips based on the STM 603 whole-footwear tribometer under different coefficient of friction testing conditions. Ergonomics 62, 668–681. [PubMed: 30638144]

Beschorner KE, Redfern MS, Porter WL, Debski RE, 2007 Effects of slip testing parameters on measured coefficient of friction. Applied ergonomics 38, 773–780. [PubMed: 17196925]

Blanchette MG, Powers CM, 2015a The influence of footwear tread groove parameters on available friction. Applied ergonomics 50, 237–241. [PubMed: 25959339]

Blanchette MG, Powers CM, 2015b Slip Prediction Accuracy and Bias of the SATRA STM 603 Whole Shoe Tester. Journal of Testing and Evaluation 43.

Burnfield JM, Powers CM, 2006 Prediction of slips: an evaluation of utilized coefficient of friction and available slip resistance. Ergonomics 49, 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: The Journal of the Human Factors and Ergonomics Society 53, 461–473.

Chang WR, 2002 The effects of slip criterion and time on friction measurements. Safety Science 40, 593–611.

Chang WR, Gronqvist R, Leclercq S, Brungraber RJ, Mattke U, Strandberg L, Thorpe SC, Myung R, Makkonen L, Courtney TK, 2001a The role of friction in the measurement of slipperiness, Part 2: survey of friction measurement devices. Ergonomics 44, 1233–1261. [PubMed: 11794766]

Chang WR, Gronqvist R, Leclercq S, Myung R, Makkonen L, Strandberg L, Brungraber RJ, Mattke U, Thorpe SC, 2001b The role of friction in the measurement of slipperiness, Part 1: friction mechanisms and definition of test conditions. Ergonomics 44, 1217–1232. [PubMed: 11794765]

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, 1118–1137. [PubMed: 11794761]

Cowap M, Moghaddam S, Menezes P, Beschorner K, 2015 Contributions of adhesion and hysteresis to coefficient of friction between shoe and floor surfaces: effects of floor roughness and sliding speed. Tribology-Materials, Surfaces & Interfaces 9, 77–84.

Grönqvist R, Matz S, Hirvonen M, 2003 Assessment of shoe-floor slipperiness with respect to contact-time-related variation in friction during heel strike. Occupational Ergonomics 3, 197–208.

Grönqvist R, Roine J, Jarvinen E, Korhonen E, 1989 An apparatus and a method for determining the slip resistance of shoes and floors by simulation of human foot motions. Ergonomics 32, 979–995. [PubMed: 2806228]

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

Iraqi A, Cham R, Redfern MS, Beschorner KE, 2018a Coefficient of friction testing parameters influence the prediction of human slips. Applied Ergonomics 70, 118–126. [PubMed: 29866300]

Iraqi A, Cham R, Redfern MS, Vidic NS, Beschorner KE, 2018b Kinematics and Kinetics of the Shoe during Human Slips. Journal of Biomechanics 74, 57–63. [PubMed: 29759653]

Jones TG, Iraqi A, Beschorner KE, 2017 Impact of Slip-Resistant Shoe Outsole Parameters on Available Coefficient of Friction, Slips, Trips and Falls International Symposium Toronto Rehab Institute, Toronto, ON.

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

Leamon TB, Son DH, 1989 The natural history of microslip. Advances in Industrial Ergonomics and Safety I, 633–638.

Moghaddam SR, Beschorner KE, 2016 Multi-scale finite element model for predicting shoe-floor hysteresis coefficient of friction of slip-resistant shoes, in: Webster M (Ed.), Society of Tribology and Lubrication Engineers Annual Meeting STLE, Las Vegas, NV.

Moore DF, 1972 The friction and lubrication of elastomers, International series of monographs on material science and technology. oxford: pergamon press.

SATRA Technology, 2019 SATRA STM 603AC Calibrated Floor Tile. Kettering, UK.

Singh G, Beschorner KE, 2014 A Method for Measuring Fluid Pressures in the Shoe-Floor-Fluid Interface: Application to Shoe Tread Evaluation. IIE Transactions on Occupational Ergonomics and Human Factors 2, 53–59. [PubMed: 31106007]

Strandberg L, 1985 The effect of conditions underfoot on falling and overexertion accidents. Ergonomics 28, 131–147. [PubMed: 3996350]

U.S. Department of Labor- Bureau of Labor Statistics, 2018 TABLE R4. Number of nonfatal occupational injuries and illnesses involving days away from work by industry and selected events or exposures leading to injury or illness, private industry, 2017, Washington, D.C.

Widas P, 2013. Newsletter: 11 8, 2013 Excel Tribometers, LLC, Chesapeake, VA.

Wilson M, 1990 Development of Satra Slip Test and Tread Pattern Design Guidelines. Slips, Trips, and Falls: Pedestrian Footwear and Surfaces, ASTM STP 1103, 113–123.

Wilson M, 1996 Slip resistance characteristics of footwear solings assessed using the SATRA friction tester. Journal of testing and evaluation 24, 377–385.

Yamaguchi T, Hsu J, Li Y, Maki BE, 2015 Efficacy of a rubber outsole with a hybrid surface pattern for preventing slips on icy surfaces. Applied ergonomics 51, 9–17. [PubMed: 26154199]

Yamaguchi T, Katsurashima Y and Hokkirigawa K, 2017 Effect of rubber block height and orientation on the coefficients of friction against smooth steel surface lubricated with glycerol solution. Tribology International, 110, pp.96–102.

Highlights

- Impact of time-interval on friction repeatability, bias, and validity was tested
- Four time-intervals (2, 50, 100 and 200 ms) were considered
- Coefficient of friction values and their repeatability were insensitive to the interval
- Results support using shorter intervals to test smaller floor samples

Author Manuscript

Author Manuscript

Author Manuscript

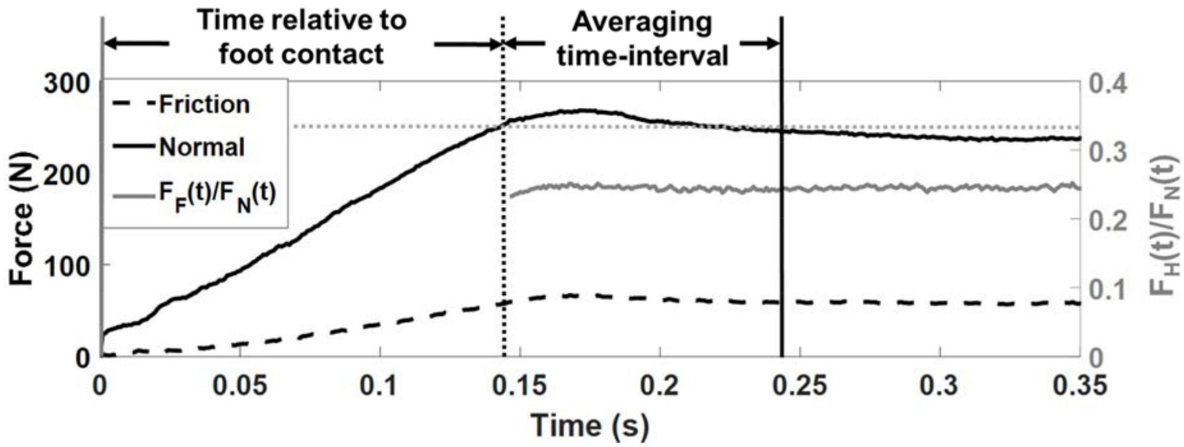

Figure 1:

Example of friction and normal forces from a shoe-floor ACOF trial with a 100 ms averaging time-interval. The vertical gray line represents heel contact; the dashed vertical line represents when the normal force first reaches the target force; the vertical black line represents the end of the averaging time-interval; and the horizontal, dashed, gray line represents the target normal force (250 N). Note that the shoe has reached steady-state sliding speed at the moment of heel contact as previously described for this test method (Iraqi et al., 2018a).

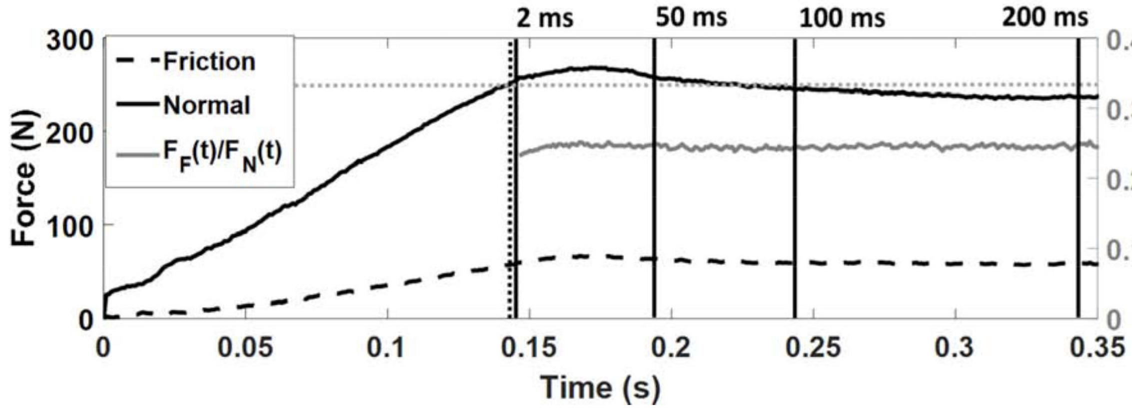

Figure 2:

A representative time-series of forces (left axis, black lines) and force ratio ($F_F(t)/F_N(t)$) (gray line, right axis). Friction ($F_F(t)$) (dotted line) refers to the vector sum of the friction force perpendicular to the sliding direction and the friction force in the sliding direction. The black, vertical, dotted line is the start of the averaging interval, which occurs when the normal force ($F_N(t)$) first exceeds the threshold (marked with the gray, horizontal, dotted line) of 250 N. The end of the averaging interval is labeled for 2 ms, 50 ms, 100 ms and 200 ms with vertical solid black lines.

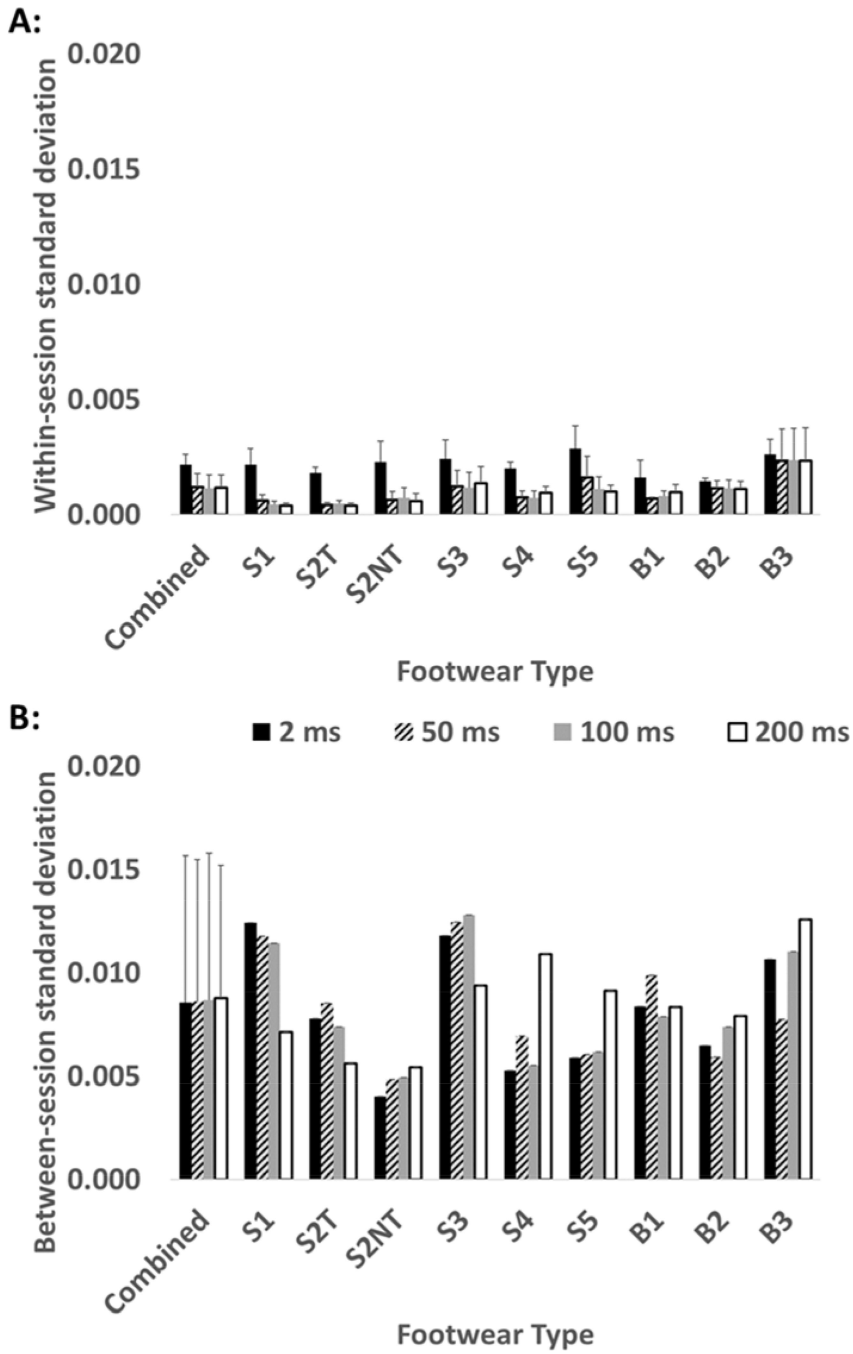

Figure 3:
Within-session (A) and between-session (B) standard deviation values for each averaging interval and footwear type. For within-session, data is averaged across sessions for each footwear. The error bars in A represent the standard deviation across session. The combined bars (A and B) represent the root mean square error with error bars representing standard deviations across footwear type.

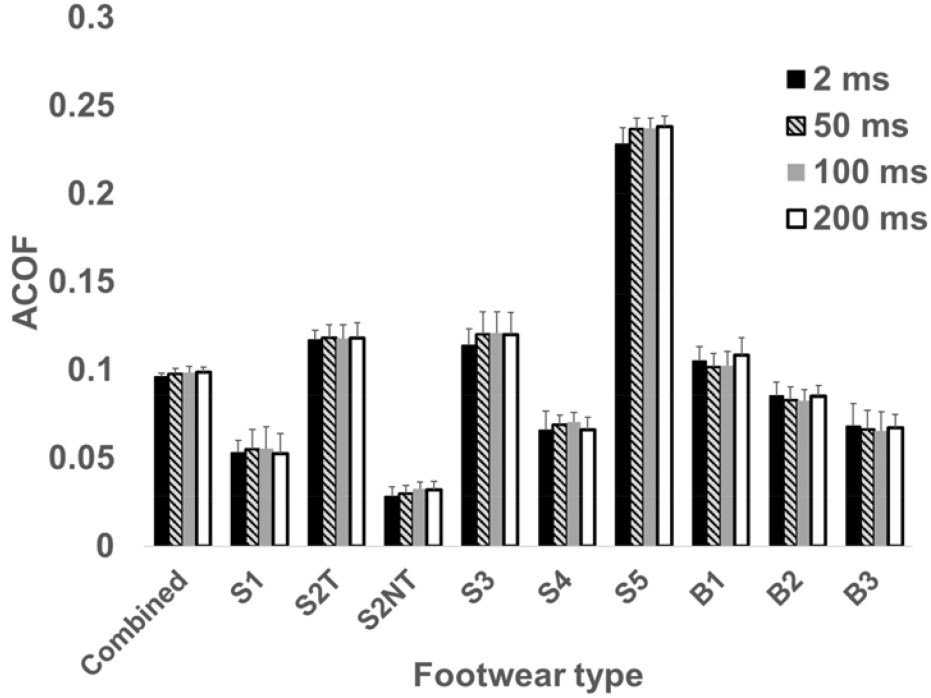

Figure 4:

ACOF values for each shoe when calculated using the different interval times. Error bars represent the between-session standard deviation. Combined represents the mean value across the nine footwear designs. The error bars for the combined represent the between-session standard deviation of these mean values.

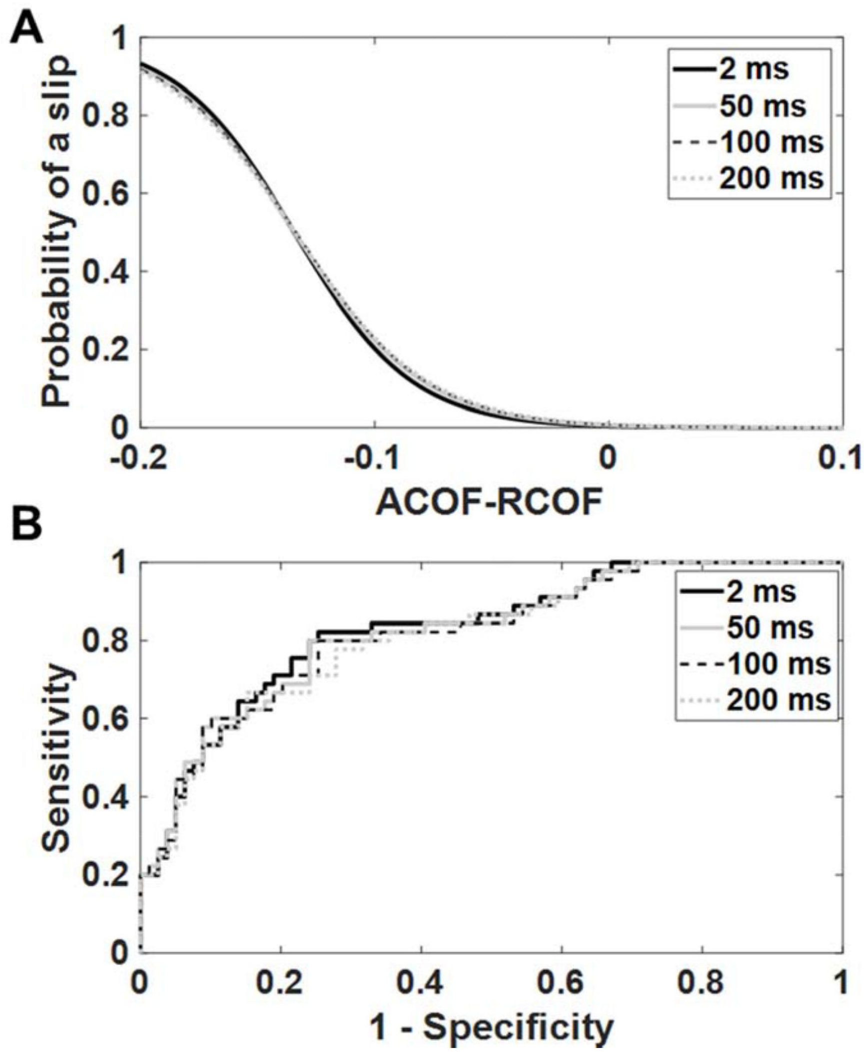

Figure 5:

A: Logistic regression fit models for the four time-intervals. B: Receiver Operating Characteristic Curves for the four time-intervals.

Table 1:

Results of the logistic regression analysis ranked from highest area under the curve (AUC) to lowest AUC. The β values represent the coefficients for the logistic regression curve (consistent with the notation described in (Iraqi et al., 2018a)). The “Optim Sens” and “Optim Spec” represents the sensitivity and specificity, respectively, corresponding to the point in the receiver operating characteristic curve that best balances sensitivity and specificity.

Rank	Averaging interval	β_0	β_1	p-value	AUC	Optim Sens	Optim Spec
1‡	2 ms	−5.36	−39.9	<0.001	0.830	82.2	74.7
2	50 ms	−4.95	−36.9	<0.001	0.823	80.0	75.9
3	100 ms	−4.85	−36.3	<0.001	0.819	80.0	74.7
4	200 ms	−4.76	−35.5	<0.001	0.815	66.7	84.8

‡Indicates a significantly higher ROC curve relative to the existing method’s averaging interval (200 ms).