Standardized Measurement of Surface Dry Particle Thickness for Walkway Slip Resistance

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Keywords: slip resistance, floors, tribometry, coefficient of friction, particles, rubbing

Abstract

Slip and fall incidents remain a critical safety concern in residential and occupational settings. While considerable research has focused on wet contamination, the role of dry contaminants in reducing floor friction has been less explored. This study establishes a standardized methodology for measuring dry particle thickness and investigates the effects of recombing dry contaminants on the coefficient of friction (COF). Using a modified tribometer and custom 3D-printed combs (127µm, 254µm, and 508µm depths), iodized salt was applied to a high-gloss tile, and COF was measured under recombed and non-recombed conditions. Results indicated that recombing significantly lowered COF, whereas non-recombed conditions did not differ from the uncontaminated tile, highlighting the necessity of recombing to accurately assess slip resistance. This study presents a cost-effective approach to slip-resistance testing, with implications for forensic investigations, industry safety standards, and workplace hazard assessments.

Keywords: **SLIP RESISTANCE, FLOORS, TRIBOMETRY, COEFFICIENT OF FRICTION, PARTICLES, RUBBING**

Highlights

- Introduces a standardized method to measure dry particle thickness for slip resistance assessment.
- Demonstrates that recombing dry contaminants reduces the coefficient of friction (COF) by 19.28% compared to not recombing.
- Provides a cost-effective, practical approach for forensic investigations and workplace hazard assessments.

Introduction

Slips and falls are considered a serious hazard in the home and the workplace [1,2]. The majority of research has focused on slip incidents induced by water contamination [3–5], oil contamination [6–12], or moving platforms [13–17]. Few studies have investigated the role of dry contaminants in slip incidents as a potential mechanism that reduces the friction between the foot-floor interface [18,19]. Understanding how dry contaminants affect the coefficient of friction (COF) can help inform maintenance standards for determining the slip resistance of floors.

Previous studies assessing floor friction under wet conditions have ensured that a continuous film of water was present before the test-foot of the tribometer contacted the tile surface [3,4,20,21]. This is important as tribometers such as the Mark IIIb, English XL, and the KSS pendulum use test foots that strike the contaminated floor and push contaminants away from the test foot, and require multiple consecutive tests to determine slip resistance. Similarly, devices like the drag sled and BOT-3000e use test foots that drag across the floor which can also push contaminants off of the surface. This methodological approach of maintaining a continuous film of contaminant after each test is important as it replicates human gait behavior in real-world scenarios, where individuals step onto a liquid contaminant rather than directly onto the flooring substrate. Ensuring a uniform liquid layer at the point of contact improves the validity of friction measurements by accurately representing the slip potential encountered in actual walking conditions.

The methodology for controlling dry substances during tribometer testing has not been established. Methodologically, one study used 10g of 5 different particle sizes that were distributed with a special comb [19]. Furthermore, this study did not replenish or recomb the particles after the tribometer test foot struck the dry contaminants. This likely affects the results, as the tribometer test foot may displace particles or change their thickness on the tested flooring surface. Another study used 500μM to 2000μM depth combs for different thickness levels of particles that ranged from 5 to 200μM in size [18]. This methodology did not state whether the particles were recombed (re-leveled) to ensure the thickness levels were the same at each strike.

Previous studies either did not replenish the particles after tribometer strikes or lacked a standardized method for ensuring consistent thickness levels. As such, the purpose of this study was to establish a standardized methodological approach to measuring the thickness of particle level and determine if there is an effect of recombing dry contaminants after each tribometer test, and thickness level of particulate matter on the coefficient of friction. We hypothesized that: (1) thinner layers of particulate matter would reduce COF more than thicker layers due to increased surface coverage, and (2) recombing would further decrease COF by ensuring consistent contaminant distribution after each tribometer strike. The results of this paper will provide a more standardized and economical approach to measuring dry contaminants' effect on slip resistance.

Methodology

One 12'' x 24'' white polished porcelain high-gloss tile was utilized for this study (Belucci Bianca, SKU 10096621, Brazil). A modified Ender-3 V2 3D printer (Creality, Shenzhen, China) with a 0.2mm nozzle utilized polylactic acid material to develop specialized combs of varying depths to control the thickness layer of particles on the tile. Three specialized combs were created with a depth of 127 micrometers, 254 micrometers and 508 micrometers, respectively (Fig. 1). Iodized table salt was used for the dry contaminants in this study. A calibrated and validated Mark III tribometer (Slip-Test, LLC, Philadelphia, PA, USA) was utilized to test the coefficient of friction.

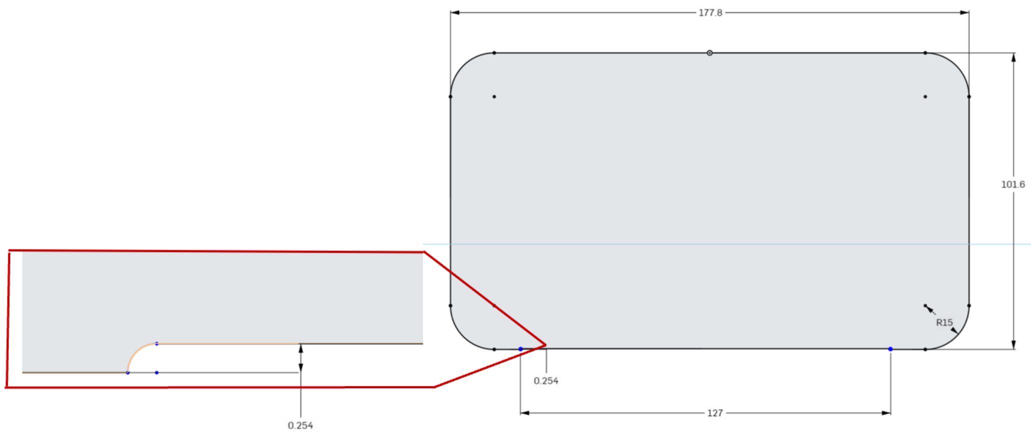

Figure 1. A schematic of the 254 µM comb. The red box shows a zoomed in perspective of the depth of the comb that allows 254 µM of material under it.

Figure 2. The three combs used in this study, 508 µM (left), 254 µM (middle) and 127 µM (right). The light coming from behind the combs allows light to pass under the comb to view the different comb depths.

Procedures

For baseline testing, the coefficient of friction of the uncontaminated tile was measured in four directions by three researchers totaling 12 COF recordings. Iodized salt was evenly spread using the 127µM comb held vertical and dragged horizontally across the tile (Fig. 3). The tribometer was placed over the leveled iodized salt so the test foot would strike the even layer. The tribometer performed multiple trials, with the test foot repeatedly striking the contaminant, to obtain a stable slip resistance measurement. For the recombing condition, the contaminant was recombed between each test foot strike with the respective depth so there was a consistent level each time the tribometer made a test foot strike. The coefficient of friction was tested in four orthogonal directions on the tile and the COF was reported for each direction as done in prior studies [3,4,20,22]. This process was repeated for 254µM and 508µM of the iodized salt. Three researchers tested each contaminant, and each thickness level of the particle, on the tile in four directions, yielding a total of 12 samples per thickness of the contaminant. For the no recombing condition, the contaminant was not recombed between each test foot strike with the respective depth and the dry contaminants distribution after each strike was not considered. The coefficient of friction was tested in four orthogonal directions on the tile and the COF was reported for each direction. This process was repeated for 254µM and 508µM of the iodized salt. Three researchers tested each contaminant, and each thickness level of the particle, on the tile in four directions, yielding a total of 12 samples per thickness of the contaminant.

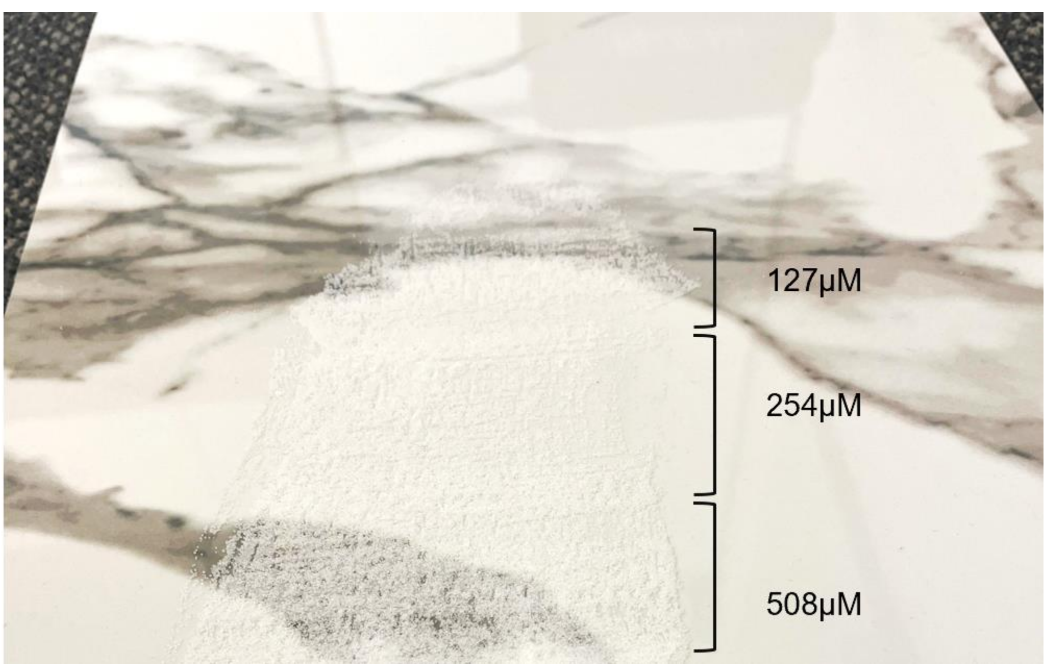

Figure 3. A photograph showing the three depth surfaces (127μM, 254μM and 508μM) of the iodized salt on the tile.

Analysis

Statistical treatments were conducted with SPSS (IBM SPSS Statistics for Windows, Version 29.0.2.0, Armonk, NY: IBM Corp). A one-way repeated measures ANOVA was conducted followed by post hoc pairwise comparisons with a Bonferroni correction to determine if the coefficient of friction was influenced by the thickness of the particle level and recombing. Significance was set to $\alpha < 0.05$.

Results

A one-way repeated measures ANOVA was conducted to evaluate the effect of combing and particle thickness on the coefficient of friction (COF) of a surface contaminated with dry particles. The seven experimental conditions included: recombed 127μm, recombed 254μm, recombed 508μm, not recombed 127μm, not recombed 254μm, not recombed 508μm, and an uncontaminated control condition.

The mean COF values for each condition were as follows: recombed 127μm (M = 0.149, SD = 0.0079), recombed 254μm (M = 0.159, SD = 0.0090), recombed 508μm (M = 0.165, SD = 0.0100), not recombed 127μm (M = 0.204, SD = 0.0178), not recombed 254μm (M = 0.189, SD = 0.0079), not recombed 508μm (M = 0.193, SD = 0.0123), and the control (M = 0.208, SD = 0.0097).

Mauchly's test of sphericity was non-significant ($W = 0.048$, $\chi^2(20) = 26.63$, $p = 0.170$), indicating that the assumption of sphericity was met, and standard F-tests were used. The repeated measures ANOVA revealed a significant main effect of condition on COF ($F(6,66) = 51.32$, $p < 0.001$, $\eta^2 = 0.823$), indicating that at least one condition differed significantly from the others.

Pairwise comparisons with Bonferroni correction were conducted. All recombed contaminated conditions had significantly lower COF than the control condition (p < 0.001, Fig. 4). There were no significant differences in COF between the control tile and recombed conditions of 127µm (p = 1.00) and 508µm (p = .394, Fig. 4). The control tile exhibited significantly greater COF than the not recombed 254µm (p = 0.02, Fig. 4). Not recombed 127µm, 254µm, and 508µm had a significantly higher COF than all recombed conditions (p < 0.001, Fig. 5). Within the recombed conditions, 127µm had a significantly lower COF than 500µm (p = 0.01, Fig. 6). Among not recombed conditions, there were no significant COF differences between 127µm and 254µm (p = 0.493, Fig. 6), 127µm and 508µm (p = 1.00, Fig. 6), and 254µm and 508µm (p = 1.00, Fig. 6).

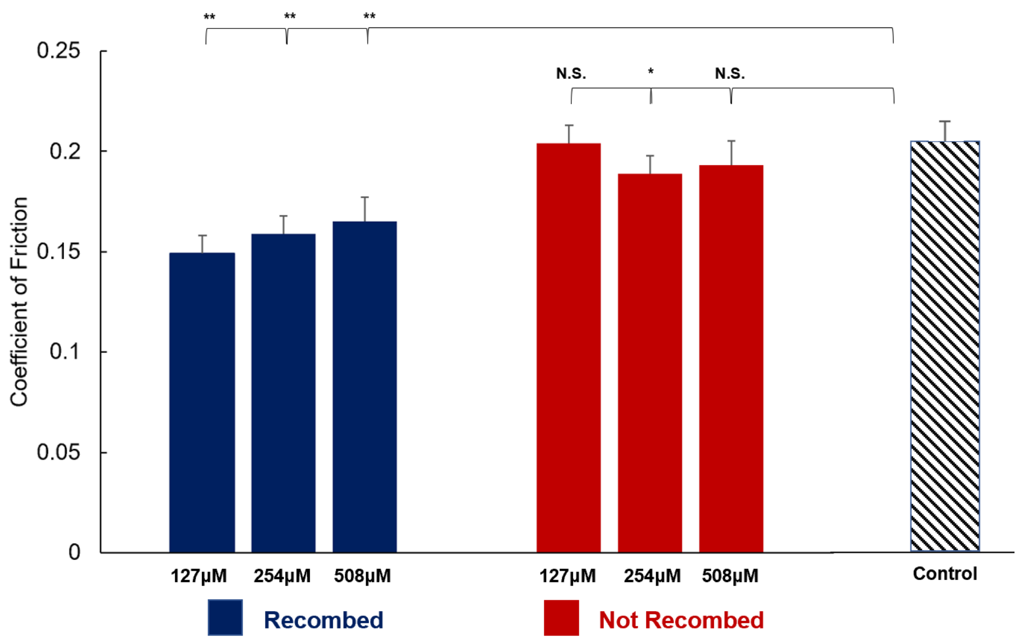

Figure 4. COF values for recombed (blue) and not recombed (red) particle thicknesses at 127µM, 254µM and 508µM compared to the tile's COF with no dry substance (control). Error bars indicate standard deviation. ** denotes significant differences at p < 0.001 and * denotes significant at p = 0.02. N.S. denotes Not Significant at p < 0.05.

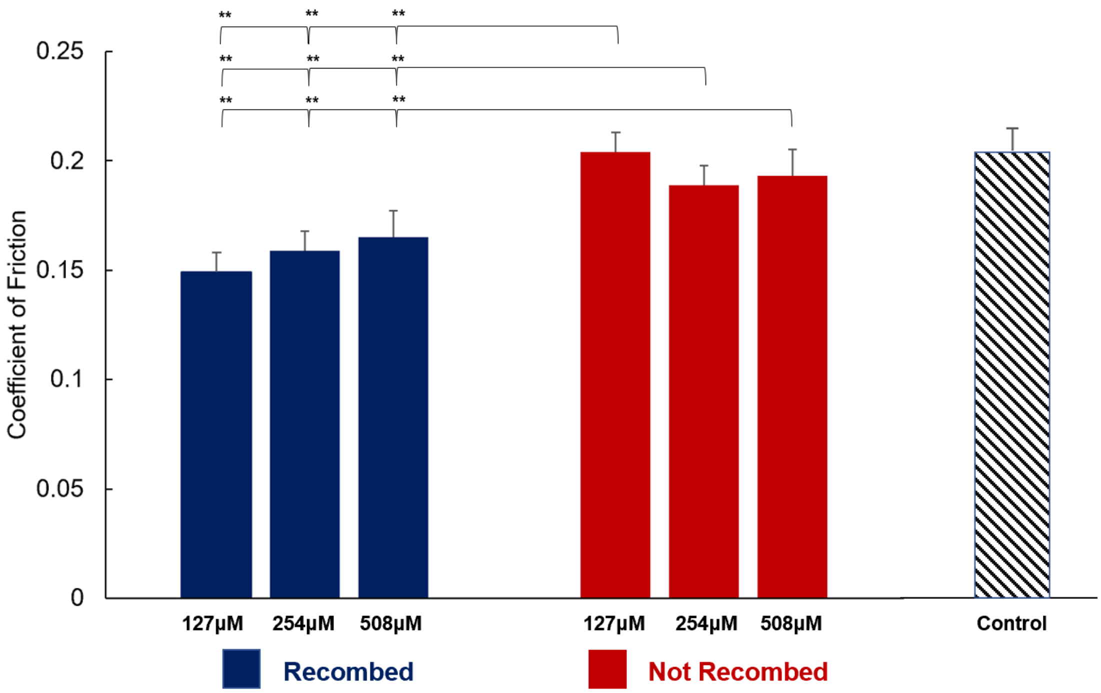

Figure 5. Particle thickness of 127µM, 254µM and 508µM comparing COF between recombed (blue) and not recombed (red). Error bars indicate standard deviation. ** denotes significant differences at $p < 0.001$.

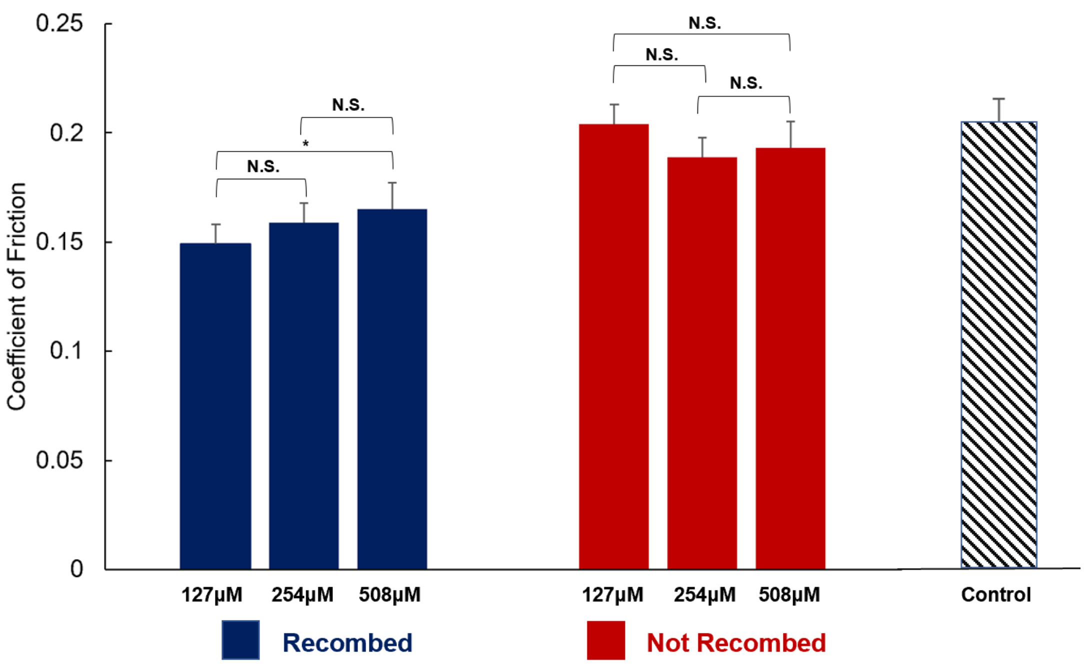

Figure 6. Particle thickness of 127µM, 254µM and 508µM comparing COF within recombed

(blue) and not recombed (red). Error bars indicate standard deviation. * denotes significant differences at $p = 0.01$. N.S. denotes Not Significant at $p < 0.05$.

Discussion

The purpose of this study was to establish a standardized methodological approach to measuring the thickness of particle level and determine if there is an effect of recombing and thickness level of particulate matter on the coefficient of friction. In support of our hypothesis, thinner levels of particulate matter resulted in a lower COF on the tile floor. Furthermore, in support of our hypothesis, particulate matter that was recombed exhibited significantly lower COF compared to particulate matter that was not recombed.

This study addressed several methodological gaps from prior research. Previous works, such as those by Li et al. (2014), did not account for the redistribution of particles between tribometer strikes which likely introduced inconsistencies in COF readings. By recombing the particles after each test, this study ensured consistent particle thickness, thereby improving the reliability of the measurements. The significant differences in COF values between recombing and not recombing layers highlight the importance of maintaining consistent particle distribution when evaluating slip resistance.

The recombing of dry contaminants is necessary for accurate representation of slip hazards on pedestrian walkways. For each given particle thickness level, the COF was significantly lower in conditions with the recombing compared to the not recombed contaminants. Furthermore, the recombed COF was significantly lower compared to the tile (not contaminated), and the not recombed COF was not significantly different compared to the tile (not contaminated). One possible explanation is that without recombing, the tribometer test foot may clear away most of the contaminant, effectively testing the clean tile rather than the contamination layer (Fig. 7). The test foot essentially strikes the tile directly and pushes the contaminants away from the test foot revealing an almost clean tile for consecutive strikes. In contrast, the recombed material was significantly lower than the control and not recombed conditions as the test foot was striking the dry contaminants each time a slip resistance test was performed, thus result in a lower COF.

Figure 7. Sequential photographs showing the progressive displacement of dry contaminants after three consecutive tribometer strikes without recombing, demonstrating the loss of uniform particle distribution over repeated trials and the accumulation of particles pushed away from the test foot striking location.

The comb-based approach developed in this study offers a novel, accessible, and cost-effective solution for standardizing dry contaminant testing. Using a 3D printer and polylactic acid material, the combs were designed and fabricated at a minimal cost, making this methodology affordable and readily available for widespread use. To ensure precision, the 3D printing process requires approximately 10 hours per comb, with slower speeds improving resolution for the 127 μm depth. This approach has the potential to be implemented in various contexts, including academic research, forensic investigations, and industry testing, without requiring substantial financial or technical resources.

Despite its contributions, this study is not without limitations. Only one type of particle (iodized salt) and one flooring material (high gloss porcelain tile) were tested. Future research should explore other contaminants (e.g., sawdust, flour, industrial powders) and flooring types (e.g., linoleum, untreated concrete) to broaden the method's applicability and determine whether similar effects are observed. Another limitation arises from the recombing methodology providing consistency, whereas real-world contamination scenarios may involve irregular distribution which could influence slip-resistance outcomes. As this study was designed to be a methodological and proof of concept study, it was not designed to address multiple contaminants and floor types.

Practically, these findings have significant implications for slip-resistance testing and floor safety standards. Dry contaminants, such as iodized salt, flour, salt, dust, sawdust, and other particles, are common in both residential and occupational environments. The demonstrated impact of particle thickness on COF highlights the need for safety protocols that account for the presence and distribution of dry contaminants. Future work could expand on these findings by investigating the effects of different particle shapes, material compositions, and rough flooring surfaces to develop a comprehensive understanding of their influence on slip resistance.

This study introduces a standardized, reproducible, and cost-effective approach and methodology for standardized dry contaminant slip-resistance testing. The use of 3D-printed combs allows for precise particle thickness control, addressing methodological inconsistencies in prior research. These findings have practical implications for safety testing, forensic investigations, and workplace hazard assessments.

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