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Slipperiness perception upon stepping and standing on a surface when barefoot or shod

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I. Introduction

The awareness of slipperiness on the foot sole is an important factor determining our perception of the environment and it has a profound effect on our movement pattern and strategy of our actions. Yet we know very little about the sensory mechanisms responsible for how slipperiness is perceived and thus how to render it using haptic technologies. Awareness of slipperiness is vital for safety in workplace and everyday contexts especially for elderly people and people with reduced sensory capabilities. In athletes it aids in maximizing performance while avoiding injuries. Research indicates that individuals can detect differences in surface properties through foot contact, which informs their gait patterns and balance strategies helping them prevent falls [1]. Therefore, haptic feedback systems that accurately convey slipperiness can enhance user experiences in various applications, such as sensory augmentation systems for assisting sensorimotor control of movement and virtual environments where users appraise surface properties through simulated interactions. The sensation is also expected to be very different between barefoot interactions and when in footwear [2, 3] which might significantly reduce our capability to appraise surface properties. Despite this, there is limited research on how footwear interferes with our ability to perceive surface slipperiness. In our study, we aimed to investigate how well healthy individuals differentiate surfaces with different friction levels when they are barefooted or shod.

II. Materials and Methods

We conducted our experiments on 12 healthy young adults (23.8±4.65 years old; 6 males, 6 females). All participants reported no history of sensorimotor disease or trauma. Our study was approved by the University of New South Wales Human Research Ethics Committee. A custom tilting platform with exchangeable transparent stepping surfaces was built to investigate slipperiness perception (Figure 1). The platform could incline up to 50° at a maximum speed of approximately 1.25°/s. It was equipped with a video camera to record sole-surface interactions and a digital inclinometer to monitor the platform's incline. We used two tempered-glass panels with different friction levels. These surfaces allowed us to create four test conditions: high-friction under both feet (HH), low-friction under both feet (LL), high-friction under the left foot and low-friction under the right foot (HL), and the reverse (LH). Participants were tested both barefoot and shod with half of the participants tested barefooted in the first session and the other half tested shod. In barefoot sessions, participants washed and dried their feet. In shod sessions, participants wore shoes (Volley® International Low). A session with a given footwear-condition consisted of friction measurement blocks and a main experiment block. In the friction measurement blocks, participants stood on test surfaces with similar friction on both sides (LL or HH), and the platform was tilted until a full slip occurred. The participants were always in a safety harness to prevent falls. The main experimental block involved testing different friction conditions in a pseudorandom order. After a participant stepped on the glass surface with a given test condition (LL, LH, HL, or HH), the platform was tilted forwards with 5° steps until the participant had a full slip or platform reached 25°. Participants were asked to look forward while stepping on platform and the room lights were dimmed to reduce any chance of visual cues. Participants rated slipperiness under both feet upon stepping and after each step of inclination.

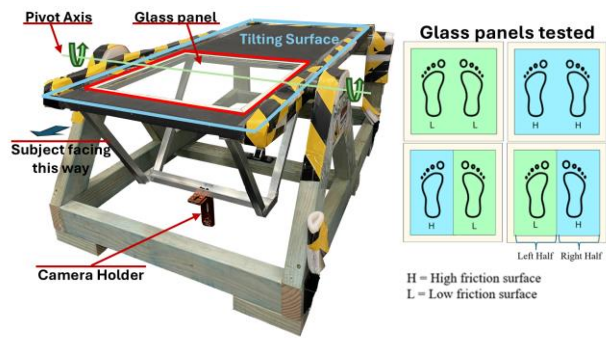

Figure 1. Custom built tilt platform and illustration of test surfaces

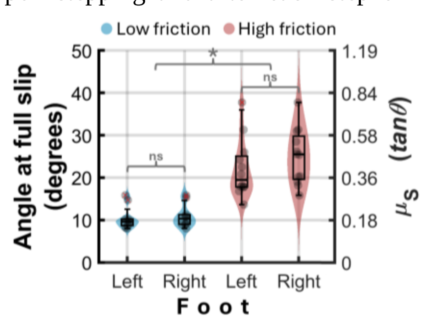

Figure 2. Coefficients of static friction of surfaces in shod condition. Asteriks: p<0.05, ns: p≥0.05.

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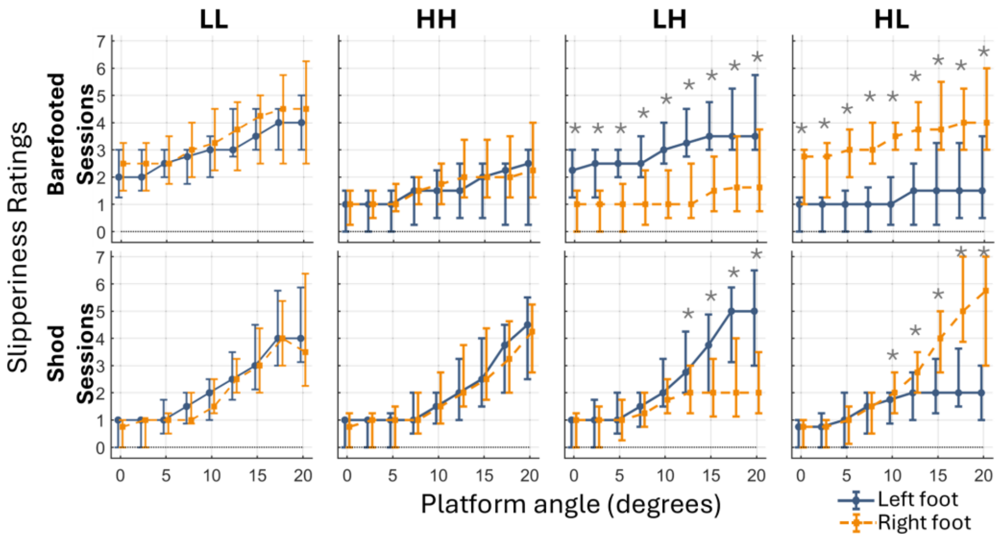

Figure 3. Slipperiness ratings in different test conditions. Data points show medians and error bars show quartiles. Asteriks indicate significant difference in slipperiness ratings between left foot (blue solid line) and right foot (orange dashed line) (p<0.05). LL, HH, LH & HL: friction conditions.

Ratings were on an open-ended scale where zero meant '*not slippery at all*'. We reported friction coefficients as mean and standard deviation and slipperiness ratings as median and quartiles. 2-way ANOVA was used to compare coefficient of friction between test surfaces and feet. Linear mixed-effects model analysis was performed to investigate factors affecting slipperiness ratings. Post-hoc analysis was performed using the Wilcoxon signed rank test with Holm-Bonferroni adjustment.

III. Results

In the friction measurement blocks, participants standing barefooted did not consistently experience a full slip up to the maximum angle at which they could comfortably remain upright. As a result, we were unable to explicitly measure friction coefficients for all participants. However, the instances where a full slip was observed confirmed the frictional difference between the test surfaces: slips occurred at lower platform angles under the low-friction condition compared to the high-friction condition. Furthermore, participants always had a full slip in the friction measurement blocks with shoes; they slipped at lower angles on low-friction surfaces (10±2.5°) compared to high-friction surfaces (24.6±4.2°) (Figure 2). The difference in static friction coefficients was significant (low-friction: 0.177±0.045; high-friction: 0.461±0.093; $F(1,44)=178.5$, $p<0.001$; quotient of high and low friction: 2.82±1.29). There was no significant difference between right and left feet measurements ($F(1,44)=1.02$, $p=0.318$). In psychophysical trials, body weight, height, and shoe size didn't have any significant effects on slipperiness ratings. The ratings given by participants who were initially tested barefoot did not significantly differ from those who were first tested wearing shoes ($F(1,1278)=1.36$, $p=0.244$). There was also no significant difference between ratings for right and left feet ($F(1,1278)=3.31$, $p=0.069$). Nevertheless, slipperiness ratings were significantly affected by friction condition ($F(3,1278)=20.27$, $p<0.001$), footwear condition ($F(1,1278)=27.61$, $p<0.001$), and inclination ($F(6,1278)=5.2$, $p<0.001$) (Figure 3). With barefoot, slipperiness ratings for LL surface were significantly higher than those for HH surface, while there was no difference in shod condition. On surfaces with different friction on right and left sides (i.e., LH and HL), participants rated low-friction surfaces as slipperier than high-friction surfaces immediately upon stepping barefoot and as the platform tilted. In contrast, participants wearing shoes rated high- and low-friction surfaces similarly until the inclination reached about 10°.

IV. Discussion and Conclusion

Our findings indicate that direct skin contact with a surface provides immediate and reliable information about slipperiness. This is enabled by limb movement kinematics, which create small displacements on the surface at the moment of contact, and by the anatomy of feet, which allows skin divergence when body weight is applied, similar to friction sensing principles proposed in fingertips [4, 5]. This cannot occur through footwear -slipping and sliding of the feet is required to perceive frictional differences. These results underscore the importance of skin sensory inputs from foot sole as potential targets for haptic interaction in various applications such as sensory augmentation devices for safety and athletic performance, virtual reality and design of footwear with enhanced sensory function in mind.

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