Texture perception at the foot sole: Comparison between walking, sitting, and to the hand

Luke D Cleland [1,2,3], **Mia Rupani** [1], **Celia R Blaise** [1,4], **Toby J Ellmers** [5], **and Hannes P Saal** [1,2,3✉]

[1]Active Touch Laboratory, Department of Psychology, University of Sheffield, Sheffield, UK; [2]Insigneo Institute for in silico Medicine, University of Sheffield, Sheffield, UK; [3]Neuroscience Institute, University of Sheffield, Sheffield, UK; [4]Cognitive Studies, Department of Philosophy, University of Sheffield, Sheffield, UK; [5]Centre for Vestibular Neurology, Department of Brain Sciences, Imperial College London, London, UK

In everyday life, we frequently interact with textured surfaces with both our feet and our hands. Similar to texture's importance for grasping, texture perception via the foot sole might provide important signals about the stability of a surface, aiding in maintaining balance. However, how textures are perceived by the foot, and especially under the high force loads experienced during walking, is unknown. The current study builds on extensive research investigating texture perception at the hand by presenting natural textures to the foot during walking and sitting, and presenting the same textures to the hand. Participants rated each texture along three perceptual dimensions: roughness, hardness, and stickiness. Participants also rated how stable their posture felt when standing upon each texture. Results show that perceptual ratings of each textural dimension were highly correlated across conditions. Hardness exhibited the greatest consistency and stickiness the weakest. Moreover, correlations between walking and sitting were lower than those between sitting and the hand, demonstrating that mode of interaction (high vs low force) had a greater impact on perception than body region used (foot vs hand). On an individual level, correlations between conditions were higher than those between participants, suggesting that differences are greater between individuals than between mode of interaction or body region. When investigating the relationship to perceived stability, only hardness contributed significantly, with harder surfaces rated as more stable. Overall, tactile perception appears consistent between body region and mode of interaction, although differences in perception are greater when interacting with textures during walking.

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Correspondence: ***ldcleland1@sheffield.ac.uk***

Introduction

Imagine waking up in the middle of the night and needing to use the bathroom. Navigating through the darkness and relying on our sense of touch, our feet effectively detect subtle differences in texture, allowing us to differentiate between the rough fabric of the bedroom carpet, the hardwood floor in the hallway, and the smooth surface of the bathroom tile. Are such judgements made through our feet comparable to texture percepts arising from our hands? The feet differ from the hands in their tactile innervation, their mechanical behaviour, and in how they typically interact with surfaces, but how perceptually relevant these factors are is hard to answer. The vast majority of research on texture perception has focused on the hands and comparatively little is known about whether and how texture perception differs across body parts, though some differences between hairless and hairy skin have been established (Ackerley et al., 2014).

Both the palmar hand surface and the foot sole are hairless skin and therefore show similar innervation characteristics. Notably, though, the foot sole contains only a quarter of the number of tactile afferents compared to the hand (Corniani and Saal, 2020), yielding markedly lower spatial acuity (Mancini et al., 2014). This might affect the perception of roughness, which relies on a spatial code for coarser textures (Weber et al., 2013). Indeed, the perception of roughness has been found to differ across hand regions (Gescheider and Wright, 2021), suggesting afferent density contributes to differences in texture perception.

There are also differences in the mechanics of the skin between the hand and the foot. Specifically, skin on the foot sole is thicker (Chao et al., 2011), harder, and more variable, than palmar skin (Falanga and Bucalo, 1993; Strzalkowski et al., 2015). It has been shown that skin stiffness directly affects discrimination accuracy for the softness of different materials (Li and Gerling, 2023), with greater stiffness leading to poorer compliance discrimination. This suggests that perception at the foot may be poorer compared to the hand due to differences in skin mechanics.

Finally, one of the largest differences between natural interactions with the external world involving our hands and feet is the mode of interaction. Texture exploration using the hands involves relatively low forces (Smith et al., 2002) and typically includes lateral movement between the skin and the surface (Callier et al., 2015; Lederman and Klatzky, 1987), while the most common mode of interaction with the foot is arguably during stepping, which involves much higher forces and less lateral movement. The force applied to a surface is especially important when judging roughness (Hollins and Risner, 2000; Lederman and Taylor, 1972), with higher forces leading to greater roughness ratings (Lederman and Taylor, 1972; Smith et al., 2002). As the foot regularly experiences forces exceeding three times body mass (Cleland et al., 2023; McKay et al., 2017), materials may be perceived as much rougher at the foot sole than at the hand.

Investigating texture perception on the foot sole is important, because textures might provide important clues about the stability of a given surface. For example, on the hand, textures have direct functional consequences for the effective interactions with objects, enabling us to hold objects without them slipping by applying the appropriate force to ensure optimal friction between our fingers and the object (Johansson and Flanagan, 2009; Westling and Johansson, 1984). The ability to distinguish between surfaces is equally important at our feet, to be able to inform us of the surface we are standing or walking on. Decoding such information allows humans to walk on stable surfaces and adjust gait to prevent falls, for example if the ground is soft or slippery (Schepers et al., 2017). Research has also suggested that increased tactile feedback from the foot sole aids balance: for example, standing on surfaces that contain small textured elements reduces par-

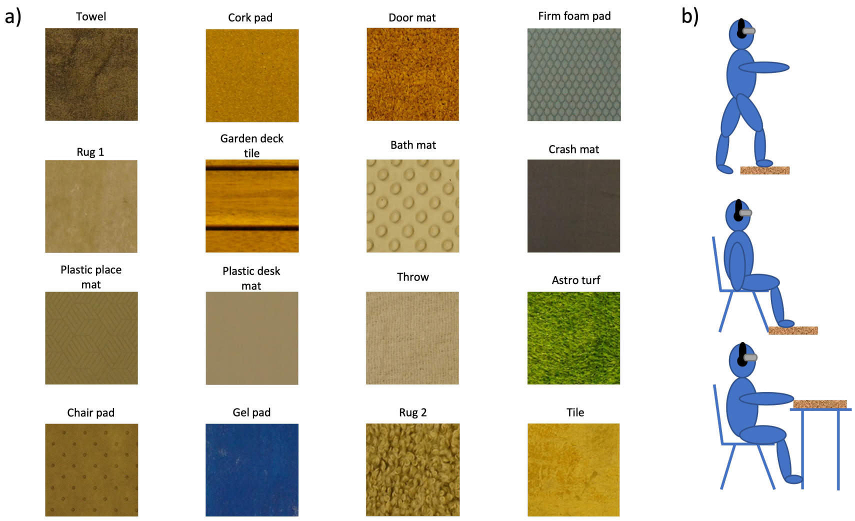

Figure 1. Overview of the textures and presentation conditions. a) A section (roughly 10x10cm) of each of the 16 natural textures used, in the experimental grid layout. **b)** Illustration of the three presentation conditions, walking (top), sitting (middle) and exploration with the hand (bottom).

ticipants' natural sway (Hatton et al., 2011; Qiu et al., 2012; Wheat et al., 2014), even though these surfaces are not inherently more stable. This effect is exploited by textured insoles that aim to improve balance (Aruin and Kanekar, 2013; Hatton et al., 2022). It has been suggested that presenting textures to the foot sole will increase tactile feedback, resulting in greater information relating to shifts in pressure(Fabre et al., 2021). In turn, these cues will improve balance and reduce the risk of falling (Kenny et al., 2019). However, which textures might be especially suited for such purpose is not entirely clear. In the hand, surface roughness is highly correlated with neural activity (Lieber et al., 2017), suggesting that roughness might be a good proxy to identify suitable textures.

Here, we investigate how natural textures on the foot sole are perceived compared to the hand. Participants rated textures along three perceptual dimensions—roughness, hardness, and stickiness—during three conditions: stepping onto the texture, gently exploring the texture with the foot sole while sitting, and exploring the texture with the hand. Participants also judged the perceived stability of each textured surface. The results provide insights into how texture perception differs across the body and under high loads, such as those experienced by the foot during gait.

Materials and methods

Participants

20 young, healthy participants (7 male, 18 female) with a mean age of 20.00 (2.66) years with no history of sensory deficits were recruited to take part in the study. One participant was unable to complete the hand condition due to illness, and therefore the within participant comparisons between the hand and foot conditions are not analysed for this participant. All participants provided informed consent prior to the start of data collection.

Textures

16 natural textures were included in the experiment (Figure 1). Textures selected are commonly experienced by the foot sole and were expected to vary across perceptual dimensions. They included those experienced in the household such as rugs, those experienced outside such as artificial grass and garden decking, along with materials commonly used during insole manufacturing such as cork and gel. All texture patches were at least 25 by 22 cm in size to allow participants to step onto and stand on a given patch with both feet. The same texture samples were used across all conditions.

Experimental protocol

Participants took part in three presentation conditions: walking, where participants stepped onto and off of the texture, exploring with the foot sole while sitting, and exploring with the hand while sitting. In all conditions, participants wore a blindfold and noise-cancelling headphones throughout the experimental session to remove visual and auditory influences on perception. During the stepping condition, participants were guided at all times using a guiding stick, receiving a tap on the hand to ask participants to step onto and off of each texture. Participants were instructed to lead with their dominant foot and make a cautious step onto the texture before pausing for two to three seconds and stepping off. As soon as participants stepped off of the texture, they stated their rating of the texture along the dimension in question (see below). For the sitting and hand conditions, participants remained seated in one location and textures were collected before being presented by the research team. Between each presentation, participants rested their feet on a foot-rest on the chair or their hands on the edge of the table for the hand condition. Participants received a tap on the leg or hand to instruct them to begin, and finish, exploring the texture, stating their rating following exploration termination. This protocol ensured that each texture was presented for between two and three seconds for all three conditions.

Participants judged each texture along one of the three main textural dimensions—roughness, hardness, and stickiness—in separate blocks, using free magnitude scaling, a method commonly used previous texture research (Hollins and Risner, 2000; Callier et al., 2015; Gescheider, 1997; Skedung et al., 2011; Boundy-Singer et al., 2017). For example, for roughness they were instructed to "rate the subjective roughness using any positive number including zero, with low numbers indicating very smooth and high numbers indicating very rough". Participants were given an example prior to the start of the first presentation: "If you rate the first surface as a three, and the second surface is twice as rough then it would be a six". The same instructions were provided for all three textural dimensions, with the wording adjusted for each dimension. For the stepping condition only, participants were also

Table 1. Texture properties

Texture number	Texture name	Material
1	Door mat	99.5% coir, 5% polyester
2	Rug 1	100% polyester
3	Towel	100% cotton
4	Rug 2	100% polyester
5	Cork pad	Cork, polyeurathene unbleached paper
6	Plastic place mat	Polypropylene plastic, polyethylene plastic, synthetic rubber
7	Chair pad	back: 100% polypropylene, inner: polyurethane foam 30kg/cu.m.
8	Bath mat	Natural rubber, calcium carbonate
9	Astro turf	Nylon, polypropylene or polyethylene
10	Plastic desk mat	Polyethylene plastic, EVA plastic
11	Garden deck tile	Acacia
12	Tile	Ceramic
13	Crash mat	Outer: nylon (230 gsm soft nylon polyester PU coated water resistant fabric), inner: polyurethane foam (5cm reconstituted foam + 5cm medium density foam)
14	Firm foam pad	100% foamed EVA
15	Gel pad	Polyurethane elastic fiber
16	Throw	40% lyocell, 39% acrylic, 21% polyester

asked in a separate experimental block to rate the perceived stability of each textured surface. Participants rated "how stable you feel when stepping onto, and off of, the texture. If you feel so unstable that you would fall, rate it as zero". Self-rated perceived (in)stability has been shown to correlate highly with actual postural sway values in healthy controls (Castro et al., 2019; Schieppati et al., 1999), particularly when eyes are closed (Schieppati et al., 1999), as in the present study. At the end of the block, participants were asked to rate how stable they would feel in "two-foot stance on a flat surface, feet shoulder width apart and holding onto a rail" for a comparison value against all textures. The researchers demonstrated this stance within the laboratory to aid participant's visualisation of such a stance.

Textures were laid out in a 4x4 pseudo-random grid for the walking condition, which was kept consistent across all participants. Participants were guided around the texture grid in a different order for each experimental block. This order of texture presentation was kept the same between participants and between conditions (walking, sitting, hand) to control for order effects of stimulus presentation and to allow for direct comparisons to be made between conditions and participants. Three blocks were run for each condition (walking, sitting, hand) and dimension (roughness, hardness, stickiness), yielding $16 \times 3 \times 3 \times 3 = 432$ textural ratings and $16 \times 3 = 48$ stability ratings in total for each participant. To speed up the experimental protocol and in order to minimize potential familiarization with the textures, the three conditions were run in a fixed order: first stepping, which was presumed the least sensitive condition, followed by exploration with the foot and finally exploration by the hand. A full experiment typically took about 90 minutes to complete.

The study protocol was approved by the ethical review board of the Department of Psychology at the University of Sheffield (protocol no. 052209).

Statistical analysis

All analysis was run in Python, using Pandas (version 1.1.2), Scipy (version 1.6.2) and Statsmodels (version 0.13.5).

As no strict rating scale was provided, participants were free to provide scores with no upper limit constraining perceptual ratings. Using free magnitude scaling allows participants to use a scale that feels natural for them, without being limited or biased through the use of an example of a maximum score. To ensure all ratings could be interpreted across participants, each rating was normalized relative to the mean rating for each condition-dimension-participant combination. This value was averaged across the three repeats, generating a 'mean ratio' for each texture-condition-dimension-participant combination. Textures were then ranked based on their mean ratio. This study aimed to identify differences between texture ranks, and therefore implemented non-parametric analyses to investigate such differences.

To investigate how reliable perceptual ratings are between participants, average inter-subject Spearman's Rho correlations were calculated on the mean ratios of each texture per participant within a given condition and dimension. To investigate whether there were significant differences between correlations, each r-value was transformed using Fisher's z-transformation before being compared.

Repeated measures, non-parametric Friedman's tests were run to identify whether there were significant differences in texture ranks on a given perceptual dimension between conditions. A significant Friedman's test was followed up by non-parametric post-hoc Wilcoxon tests.

To investigate the relationship between the perception of textural properties and participants' perception of stability, a linear regression was run to investigate the contribution of the three textural properties, roughness, hardness and stickiness, in explaining perception of stability ratings during stepping onto and off of each texture.

Results

We presented 16 textures to 20 participants across three different conditions: walking, where participants stepped onto and off a texture with bare feet; sitting, where participants explored the textures with their feet; and finally a condition where participants explored the textures with their hands (see Methods for details). In each condition, participants judged the roughness, hardness, or stickiness of the textures in separate experimental blocks using free magnitude scaling. These three textural dimensions were chosen, because they are among the most prominent in texture studies focusing on the hand (Hollins et al., 2000; Okamoto et al., 2013) and might conceivably influence our perception of stability.

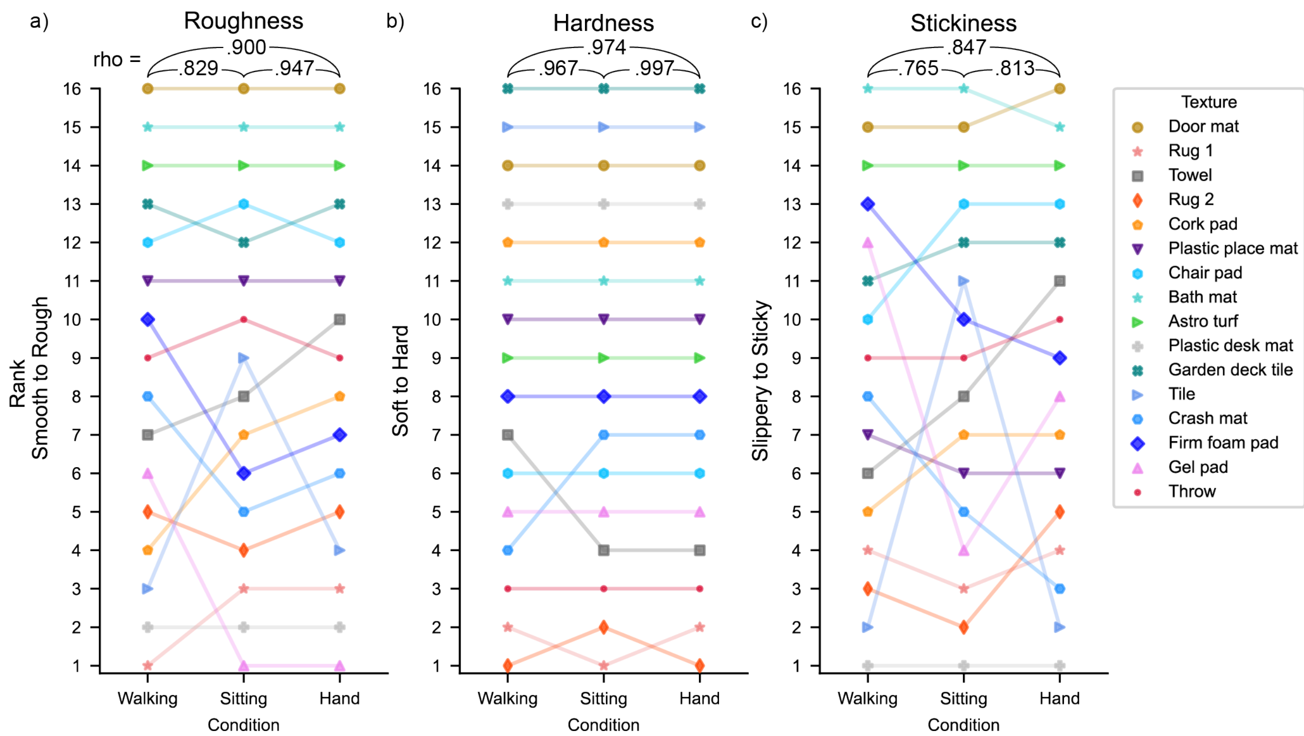

Figure 2. Group level perceptual ratings across different interaction conditions. Slope charts showing texture ranks calculated from normalised perceptual ratings averaged across participants for **a)** roughness, **b)** hardness, and **c)** stickiness. Spearman's Rho correlations between conditions displayed at the top of each plot. All correlations are significant with $p < .001$.

Group level results

As the different interaction conditions were run in separate blocks, most of the subsequent analysis will consider each texture's rank for the textural dimension in question to allow meaningful comparisons across conditions. In a first analysis, we averaged textural ratings after normalising them across all participants and then compared their ranks across interaction conditions.

We found that perceptual ratings for each textural dimension were highly correlated across conditions (Figure 2). Hardness was the most highly correlated dimension (all r>.96), with texture rankings nearly identical whether participants walked onto them, or explored them with their foot or hand (Figure 2b). For roughness, perception of very rough materials was consistent across conditions, although there was greater disagreement for smoother textures. Correlations were lower between walking and sitting compared to sitting and the hand, though overall agreement was still high (all r>.82). Stickiness ratings were the least consistent across conditions (all r>.76), with one texture (tile) moving nine ranks in the sitting condition.

Overall, while textures were generally ranked similarly, independent of body region or mode of contact, the correlation between the walking and sitting conditions was typically lower than the correlation between the sitting and hand conditions, suggesting a stronger impact of mode of interaction on perception than body region.

Consistency within and across participants

Next, we investigated whether and how the responses of individual participants were correlated between conditions and with those of other participants. Across participants, perceptual ratings were highly correlated for all conditions and textural dimensions (Figure 3b). The strongest correlations occurred for the hardness metric across all presentation conditions, with the highest overall agreement in the walking condition (average r = .80). Stickiness possessed the weakest correlation for all presentation conditions, but had greater between-participant consistency for the hand. Overall, the consistency of responses was primarily determined by the textural dimension, rather than the body part used for exploration (hand vs foot) or the method of presentation (high vs low force).

Notably, average participant-level correlations between conditions were greater than the inter-subject correlations (Figure 3b). Comparing the correlation coefficients across participants with those obtained within participants, stickiness ratings were significantly less consistent between participants than between interaction conditions within the same participants (t=2.39, p=.017). While the same pattern exists for roughness (t=0.73, p=.466) and hardness (t=1.37, p=.170), the differences between the correlations are not statistically significant. Thus, texture perception is at least as consistent between body regions and modes of contact within a given participant, than it is between participants.

When focusing on between-condition correlations at the participant level, correlations between the sitting and hand conditions are always stronger than the correlations between the other conditions, in agreement with the group level results. This further supports the notion that a similar mode of interaction with a texture will yield similar percepts, regardless of whether the foot or hand is used.

Differences between interaction conditions

Next, we further investigated differences between interaction conditions, by testing whether texture ranks differed significantly between conditions. For roughness, Friedman's tests revealed significant differences for four textures in the middle of the smoothness-roughness spectrum (Figure 4a). Post-hoc tests revealed that almost all differences occurred between the walking condition and either the sitting or the hand condition.

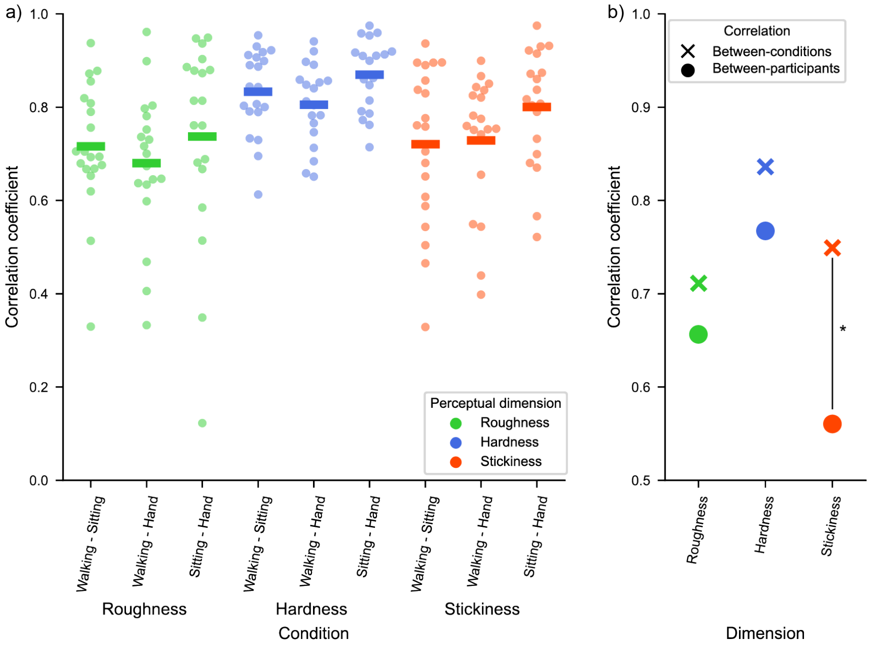

Figure 3. Between-participant and between-condition correlations. a) Between-condition correlations for each participant. Each point represents the correlation in perceptual ratings between two conditions for a given participant. The horizontal line represents the mean correlation across all participants. **b)** Comparison of average between-subject (circles) and between-condition (crosses) correlations for each perceptual dimension. An asterisk indicates a significant difference.

Table 2. Post-hoc Wilcoxon tests run on textures with significant Friedman's test. Statistic show W value. * indicates *p*<.050, ** indicates significant following Bonferroni correct for multiple comparisons, *p*<.016

Dimension	Texture	W-S	W-H	S-H
Roughness	Firm foam pad	**33.5****	**31.5***	85.5
	Towel	63.5	**24.5****	49.5
	Cork pad	**36.5***	**23.5****	69.0
	Tile	**18.0****	66.0	**32.5****
Hardness	Garden deck tile	34.5	23.0	44.0
	Crash mat	**3.0****	**1.0****	**34.5***
	Towel	**23.0***	**32.0***	48.0
	Plastic desk mat	46.0	48.0	47.0
Stickiness	Crash mat	**34.0***	47.0	59.0
	Firm foam pad	**38.0***	**22.0****	77.5
	Towel	32.5	**21.0****	**35.0***
	Tile	**22.0****	73.0	**21.0****
	Gel pad	**13.0****	37.0	**28.0***

Only one significant difference, for the tile, occurred between the sitting and hand conditions (see Table 2 for details). For hardness, Friedman's tests revealed significant differences in rank for four textures (Figure 4b), though post-hoc tests were only significant for two textures. Again, most of the differences involved the walking condition. Finally, for stickiness perception, significant differences were found for five textures (Figure 4c), with these spread relatively equally across conditions. Overall, as differences often involved the walking condition, this might suggest that they were driven more by the mode of interaction (low vs high force) rather than the fact that a different body region was involved (hand vs foot).

Notably, when a texture was judged differently across conditions, this often occurred along multiple textural dimensions: the towel yielded significant differences across all three textural dimensions, and the tile, firm foam pad, and crash mat differed across two dimensions each. Moreover, rank changes across conditions for these textures appeared correlated across textural dimensions: the tile differed the most in the sitting condition for all three textural dimensions, while the walking condition was most different for both the crash mat and the firm foam pad. These observations might imply that perceptual differences, either induced by a different body region or by a different mode of interaction, lead to correlated shifts across a number of perceptual dimensions. Due to the low number of textures with clear differences in the current study, such a claim would need to be followed up in future research.

So far, our analysis has focused on texture ranks, rather than their ratings directly. Since ratings were collected in different blocks for different interaction conditions, they might not be directly comparable. However, we can instead investigate whether the spread of responses, e.g. how much rougher the roughest texture feels compared to the smoothest one, differs across conditions. We found that the spread of perceptual scores differed between presentation conditions for roughness and hardness (Levene's tests of equality of variance; F = 17.63, p<.001 and F = 15.36, p<.001 respectively, Figure 4d, e). Specifically, perceptual roughness ratings during walking were spread further (Figure 4d) compared to the sitting and hand presentation conditions. On average, the roughest texture was rated as just over 10 times rougher than the smoothest texture during walking. In contrast, during the sitting and hand conditions, the roughest texture rated at just over, and just under, five times as rough as the smoothest texture, respectively. This suggests that roughness levels were magnified when walking, making textures seem rougher than when perceiving them with the hand or under low forces during sitting. The same pattern was evident for hardness perception, with increased spread of the responses during walking. In contrast, the distribution of responses for stickiness perception was equal across all conditions (F = 0.37, p=.692, Figure 4f).

Textural dimensions and stability ratings

To investigate whether and how any of the textural dimensions are related to perception of stability, we regressed average perceptual ratings for the different textural dimensions onto the stability ratings for each texture, both independently and jointly. For roughness, stability ratings quickly plateaued with increasing roughness (Figure 5a), leading to low explanatory power ($R^2 = 4\%$). The relationship between hardness

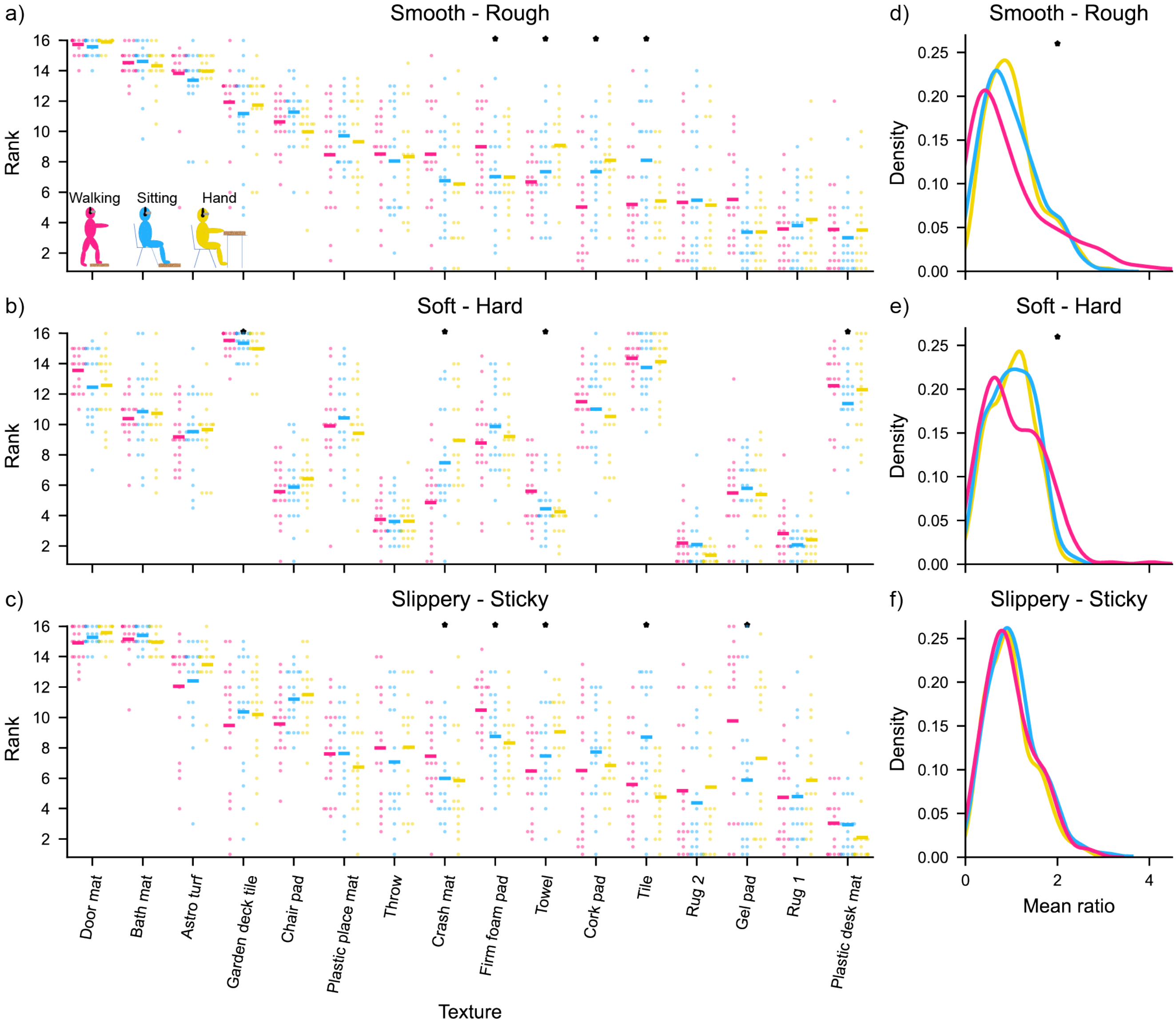

Figure 4. Differences in perception between conditions. Left panels: Participant rankings for each texture for **a)** roughness, **b)** hardness and **c)** stickiness, sorted by mean roughness rating. Mean ranks are indicated by horizontal lines. Individual points denote ranks for single participants. Asterisks indicate significant Friedman's tests showing a difference in ranks between conditions. **Right panels:** Kernel density plots showing the distribution of responses for **d)** roughness, **e)** hardness and **f)** stickiness. Asterisks indicate significant Levene's tests for equal variance.

and stability appeared linear (Figure 5b), with perceived stability being greater with increasing hardness, explaining 36% of the variance in stability ratings. There was no evident relationship between stickiness and perceived stability (Figure 5c; $R^2 = 0\%$). Finally, running a multiple linear regression, using roughness, hardness and stickiness as input variables and stability as the output variable explained 42% of the variance in stability ratings. However, only hardness contributed significantly ($p = 0.05$).

Discussion

The current study investigated texture perception at the foot sole, investigating three textural dimensions—roughness, hardness and stickiness—under different contact conditions (walking vs gentle exploration with the foot sole) and body region (foot vs hand). On both the group and individual level, perception was highly correlated across all conditions and textural dimensions. In fact, correlations between conditions were stronger than correlations between participants, indicating more consistent ratings within a given participant across interaction mode and body region than between different individuals for the same condition. Nevertheless, a subset of individual textures showed systematic differences across conditions, with the biggest shifts induced by the walking condition. Texture ratings were also spread more widely in this condition, suggesting that most of the differences in texture perception observed on the foot is likely due to the difference in contact mode rather than an inherent property of this skin site. The results also suggested that hardness is the only perceptual dimension that contributes to participants' perception of stability, with neither roughness nor stickiness ratings yielding significant correlations.

Body region

We found that texture perception was broadly consistent between the hand and the foot, with high correlations between all tested conditions for all three textural dimensions. Indeed, when there were differences, these were rarely grouped

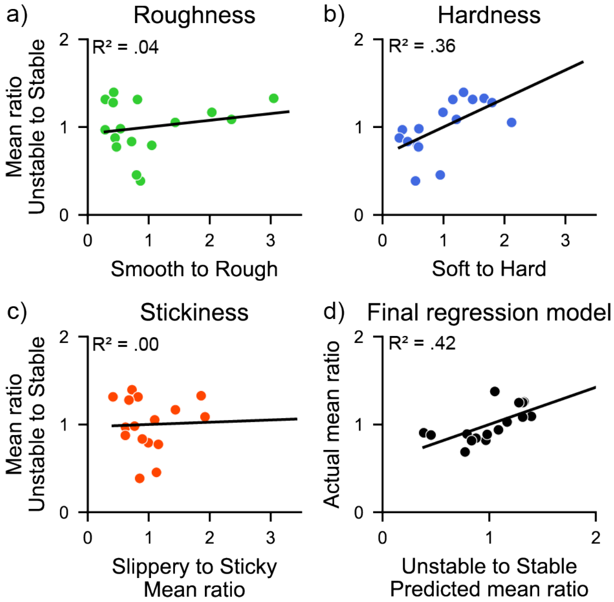

Figure 5. Relationship between textural dimensions and perceived stability. a) The relationship between perceived roughness and stability. **b)** The relationship between perceived hardness and stability. **c)** The relationship between perceived stickiness and stability. **d)** Predicted stability ratings from the multiple linear regression model compared to recorded ratings of stability. Each point reflects a single texture, showing average scores across all participants. Lines denote lines of best fit.

by body region, but instead appeared to depend on specific modes of interaction (such as walking, see further discussion below). In agreement with these findings, correlations between conditions within the same participants were generally higher than those between participants. At the same time, the between-participant correlations in the present study were comparable to those established previously. For example, Richardson et al. (2022) used a comparable natural texture set, which they asked participants to explore actively with their hands. The authors found a correlation of $r = .70$ in similarity ratings between participants, which the results of the present study are in line with.

Mode of interaction

We found that changing the mode of interaction, from gentle exploration with the foot sole to stepping onto and off the texture, led to greater changes in texture perception than using a different body region, that is switching from the hand to the foot. This difference was manifested in lower correlations of perceptual ratings in the walking condition with the other two conditions, but also an expansion in the range of responses for roughness and hardness.

One major difference in the walking condition was arguably the much higher forces acting on the foot during stepping compared to seated exploration, which might explain some of these differences. Indeed, texture perception on the hand is known to depend on the force applied, with higher forces increasing the perception of roughness (Lederman and Taylor, 1972; Smith et al., 2002).However, forces investigated in previous research on the hand are minute compared to those experienced by the foot during everyday behaviour, which regularly exceed body mass more than three-fold (Cleland et al., 2023). Another difference was that participants were able to use exploratory stroking movements when touching the texture with their hand or the foot when seated. Such active exploration has been shown to influence texture perception on the hand when compared to static presentation, for example for stickiness (Grierson and Carnahan, 2006) and roughness (Hollins and Risner, 2000). When walking, deliberate low-force exploratory movements are not possible. However, walking might also not resemble static presentation conditions. This is because considerable shear forces are present throughout the gait cycle (Tappin and Robertson, 1991), as the foot rolls from heel to toe. These stretch cues might provide relevant information beyond that available during purely static contact. After all, despite the differences seen in the walking condition, these were relatively small, suggesting that texture perception is broadly similar across all interaction conditions.

Relating textural dimensions to stability

Humans must be able to maintain balance when walking or standing on range of surfaces to prevent falls and subsequent injury. Textural cues might provide relevant, rapid hints regarding the current surface, and therefore contribute to perceived stability. For example, slippery or very soft surfaces might be perceived as less stable. However, out of the three textural dimensions investigated in the current study, only hardness contributed significantly to perceived stability, explaining about 40% of total variance in stability ratings, with harder surfaces rated as more stable. Previous research has reported similar decreases in perceived stability in older adults when standing on soft (e.g. foam) rather than hard surfaces (Anson et al., 2019). Interestingly, when controlling for *actual* changes in postural sway, older adults who had previously fallen experienced the greatest decreases in perceived stability from hard-to-soft surfaces. The authors suggested that this may have been driven by increased fear of falling experienced by those who had previously fallen, given that experimentally-induced fear of falling is known to make people feel less stable (Cleworth and Carpenter, 2016; Ellmers et al., 2022). Future work should look to explore if these relationships are driven by changes in hardness perception. For instance, do older adults who have fallen rate 'hard' textures as softer, and does this underpin the more pronounced changes in perceived stability when standing on soft surfaces? Does fear of falling alter our perception of texture hardness, leading to textures previously perceived as hard to now be experienced as softer? Recently developed VR paradigms (Cleworth et al., 2016; Ellmers et al., 2024; Raffegeau et al., 2020) could help answer these questions.

Neither roughness nor stickiness showed any relationship with perceived stability in the present work. This might suggest that texture only plays a limited part in perceived stability or that these cues are processed in a more complex, perhaps nonlinear way. However, it should be noted that the textures used in the current study did not pose any serious threat to participants' stability. For example, no extremely rough, unstable (e.g. gravel) or extremely slippery surface (soapy, wet tile) was included in the study. It is therefore possible that texture at the extreme ends of the spectrum does play a greater part in the perceived stability. Nevertheless, even the textures used in the current study yielded a wide range of stability ratings, which could not be fully explained by texture alone.

Recent research has begun to explore the use of textured insoles to improve balance (e.g. Aruin and Kanekar, 2013; Hatton et al., 2022; Robb and Perry, 2022), following the hypothesis that increased tactile feedback aids balance. Such textured insoles have been shown to reduce postural sway (Kenny et al., 2019), especially when standing on an unstable surface such as foam (Qiu et al., 2012). The majority of these interventions currently focus on using rough textures; as we did not find any relationship between roughness and perceived stability per se, it is likely that these insoles act via a more indirect mechanism, such as generally elevating the level of tactile feedback and subsequent muscle activity (Robb et al., 2021; Robb and Perry, 2022). Indeed, roughness is highly correlated with neural activity in the hand (Lieber et al., 2017), suggesting that textures perceived as very rough might make good candidates for insoles, taking into account the fact that they will feel even rougher during walking, as shown in this study.

Limitations

The current study aimed to strike a balance between presenting a diverse set of textures, assessing texture perception along a variety of dimensions, and allowing for broad comparisons between the foot and the hand, but also different modes of texture interaction of the foot itself. As such, the texture set was necessarily rather limited. For example, we only used textures that did not pose any serious threat to participants' stability to ensure the safety of participants and maintain a focus on texture perception. As a consequence, the relationship between texture and stability needs to be interpreted with this limitation in mind and it is possible that more challenging or balance-threatening textures might contribute differently to stability (see discussion above). The textures were selected as they are commonly encountered in everyday life. However, as a consequence, their properties were not carefully controlled as is possible with artificial texture sets, and their overall diversity precludes testing the perception of subtly different textures. While one prior study has investigated the ability to discriminate between similar textures (Ofek et al., 2018), further research is required to get a complete picture regarding the capability of tactile system on the foot sole. Such future research might also directly compare texture perception on different body parts or via different interactions by presenting participants with pairs of textures during a single trial. However, such experiments are data-intensive; in the present study, our focus was on investigating texture perception on the foot sole as broadly as possible. A further limitation relates to the lack of objective postural stability measure (e.g. trunk instability when stepping onto or off the textured surfaces). However, as we were interested in how different textures affected perceptual outcomes (rather than posture itself), we do not deem this a major limitation. Further, previous work has shown strong correlations between perceived and objective postural (in)stability outcomes (Castro et al., 2019; Schieppati et al., 1999)—particularly when eyes are closed (Schieppati et al., 1999), as in the present study. Nonetheless, future work should look to explore how texture perceptions interact with objective postural control outcomes.

Code and data availability

All raw data and code used to analyse the data can be found at DOI: 10.17605/OSF.IO/SP8K2.

Author contributions

L.D.C.: conceptualisation, methodology design, data curation, formal analysis, visualisation, writing and reviewing the manuscript. M.R. and C.R.B: data curation, reviewing the manuscript. T.J.E.: methodology design, writing and reviewing the manuscript. H.P.S.: conceptualisation, methodology design, supervision, writing and reviewing the manuscript.

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