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Short Paper

Submillimeter Lateral Displacement Enables Friction Sensing and Awareness of Surface Slipperiness

Naqash Afzal, Emma Stubbs, Heba Khamis, Alastair J. Loutit, Stephen J. Redmond,
Richard M. Vickery, Michaël Wiertlewski, and Ingvars Birznieks

Abstract—**Human tactile perception and motor control rely on the frictional estimates that stem from the deformation of the skin and slip events. However, it is not clear how exactly these mechanical events relate to the perception of friction. This study aims to quantify how minor lateral displacement and speed enables subjects to feel frictional differences. In a 2-alternative forced-choice protocol, an ultrasonic friction-reduction device was brought in contact perpendicular to the skin surface of an immobilized index finger; after reaching 1N normal force, the plate was moved laterally. A combination of four displacement magnitudes (0.2, 0.5, 1.2 and 2 mm), two levels of friction (high, low) and three displacement speeds (1, 5 and 10 mm/s) were tested. We found that the perception of frictional difference was enabled by submillimeter range lateral displacement. Friction discrimination thresholds were reached with lateral displacements ranging from 0.2 to 0.5 mm and surprisingly speed had only a marginal effect. These results demonstrate that partial slips are sufficient to cause awareness of surface slipperiness. These quantitative data are crucial for designing haptic devices that render slipperiness. The results also show the importance of subtle lateral finger movements present during dexterous manipulation tasks.**

Index Terms—Friction, perception, incipient slips, tactile afferents, haptics, dexterity, object manipulation, hand.

I. INTRODUCTION

Epicritic tactile perception requires exploratory scanning (sliding movement) from the fingers over the surfaces. One of the key perceptual dimensions of surface material properties is its slipperiness, since friction influences how fingertip skin interacts with the surface. During the interaction, the skin stretches and compresses under the influence of friction and the stick and slip events evoke specific spatio-temporal vibration patterns. However, when we grip objects and tools for the purpose of dexterous manipulating the relative movement between skin and the surface is much more subtle. Typically, there is no overt slip or sliding present, yet at some point during manipulation we become consciously aware of the slipperiness of the object we hold in hand. In our previous study [1] we found that humans cannot perceive frictional differences in passive touch conditions without lateral sliding movements. Even in the presence of tangential forces contacting the finger at an approach angle of 20 or 30° relative to normal to induce shear and use of various surface topography features to enhance sensory stimuli, the discrimination performance did not improve. In the same study it was also demonstrated that lateral movement of 5 mm enabled subjects to perceive frictional differences between two smooth surfaces. Thus, a full slip was sufficient.

It is not known whether a full slip is required, or under similar conditions, how much lateral movement would create awareness of frictional differences. However, this knowledge is important for applied purposes, such as friction rendering in haptic devices, and fundamental to our understanding of sensory processes underlying human perception and motor control. During reaching and gripping, natural finger positions would rarely be perfectly perpendicular to an object, unlike a well-controlled experimental set-up with the finger immobilized. Thus, subtle lateral movements of submillimeter or millimeter range are expected. Could those movements potentially be the key enabling us to feel surface slipperiness? The aim of this study is to find out the smallest movement that can elicit a conscious perception of slip. Another factor of interest is the speed of displacement, which might influence the ability to extract frictional information by affecting the extent of engagement of fast adapting tactile receptors.

In this study, we have designed an experiment that aims to test whether subjects can explicitly perceive frictional difference, by asking subjects which of two stimuli is more 'slippery'. By testing four displacement distances (0.2, 0.5, 1.2, 2 mm), we will evaluate the magnitude of lateral finger movement necessary to feel surface slipperiness. We will also examine how different speeds (1, 5, 10 mm/s), varying 10-fold, affect the thresholds of displacement at which subjects can differentiate the frictional properties of two surfaces.

II. MATERIAL AND METHODS

A. Subjects

Subjects were 12 naïve, healthy volunteers (UNSW students and researchers), without any known neural or perceptual deficits which might have affected their ability to perform experimental tasks. They were between the ages of 21 to 42, and the gender breakdown was seven men and five women. Ethics approval was obtained from the UNSW Human Research Ethics Committee (approval number: HC180109), and participants gave their informed, written consent to participate in this study.

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B. Frictional Difference Using Ultrasonic Friction Modulation

An ultrasonic friction reduction device was used to change the frictional properties of a surface through ultrasonic vibration [2]. The borosilicate glass plate's dimensions were 71 x 70 x 10 mm, and it was driven via three piezoelectric actuators glued to the glass surface. The plate's frame was mounted to the 6 axis ATI force-torque sensor, which measures the interaction efforts that the finger exerts on the plate. As the vibrating glass encounters the fingertip, the skin bounces against the plate, leading to a slight levitation of the skin from the surface of the plate. This film of air between fingertip and surface supports some of the interaction forces, thus reducing frictional resistance, and causing increased 'slipperiness'. The friction modulation plate was driven with a frequency of 33150 Hz and a maximum amplitude of 400 $V_{p\text{-}p}$. To alter the frictional properties of the plate, amplitude was adjusted, where higher amplitudes result in lower friction. Specifically, two frictional levels were implemented using 0% and 70% of the maximum amplitude which rendered physiologically relevant frictional differences and ensured optimal performance of the friction modulation device.

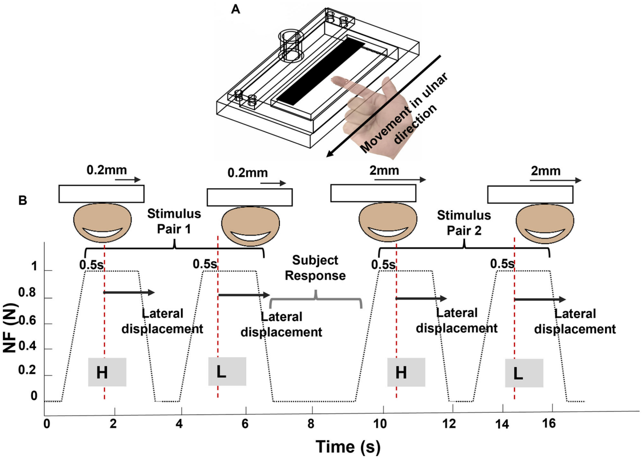

Fig. 1. Experimental protocol and apparatus. (a) Friction reduction device attached to the ATI force sensor (b) Illustration of the experimental protocol and force stimulation to the fingertip.: H is high friction and L is low friction: The lateral displacement is varied among the pairs. Red vertical line indicates the onset of lateral movement after 0.5 sec normal force (NF) plateau.

C. Experimental Apparatus

The stimuli were applied to the fingertip using a Hexapod positioning device (Physik Instrumente (PI) GmbH & Co. KG, Germany). The Hexapod is a programmable positioning device which has six degrees of freedom. Its control was implemented using a MATLAB (Mathworks, MA, USA) command interface. The Hexapod learns a force trajectory for each fingertip it encounters; that is, it learns the required distance it must move to attain the target force within the desired time period. The above-mentioned friction reduction device was attached to the Hexapod to present stimuli to the fingertip. A Powerlab series 16/35 (ADInstruments, Bella Vista, Australia) paired with LabChart software version 7.3.8 (ADInstruments, Bella Vista, Australia) were used to record force and torque applied to the friction modulation plate in x, y and z directions; friction modulation plate amplitudes; hexapod position, and button press responses.

D. Experimental Protocol

The psychophysical study used a two-alternative forced-choice (2AFC) protocol. Subjects were presented with pairs of lateral movement stimuli, one high and one low friction, with their respective order pseudo-randomized between trials. Following the completion of the second stimulus, subjects were asked to press either button 1 or 2, to indicate whether they thought the 1st or 2nd stimulus was slipperier. Subjects wore noise-cancelling headphones to prevent any auditory cues from the equipment.

The right index finger of subjects was fixed by gluing the fingernail to a rigid fingertip holder attached to the Hexapod's support table facing, anterior surface upwards. This effectively immobilized the finger, ensuring that contact between the finger and the stimulator was made at the same position and angle throughout the experiment. Subjects were instructed to remain still for the duration of the experiment, to assist with hexapod learning protocols, as well as ensuring that stimuli were identical throughout the experiment. The Hexapod lowered the ultrasonic friction reduction device down onto the anterior surface of the fingertip under computer control. Once the plate exerted its target normal force of 1 N, there was a 1.5 second period of normal force stabilization where the force was maintained at 1 N. The plate was subsequently moved laterally in the ulnar direction, following a pseudo-random schedule of four lateral distances (0.2, 0.5, 1.2, and 2 mm) and three speeds (1, 5 and 10 mm/s). Stimuli within the same pair always had the same speed. At the completion of the lateral slip stimulus, the plate was retracted. This process was repeated at regular intervals, in pairs of stimuli, implementing a pseudorandom schedule of low and high friction conditions. Fig. 1 illustrates the experimental protocol. Subjects were presented with 12 blocks of 20 trials each total. Subjects were given short breaks after every seven-minute experimental block, and a 15-minute break after the sixth block (mid-experiment). This was to prevent a loss of attention and focus, and tactile desensitization.

E. Friction Measurements

The static coefficient of friction (μ) was measured at the start and end of each block for each subject. In these trials the ultrasonic friction reduction device was lowered onto the finger until it reached 1 N normal force, after a plateau of 0.5 sec the plate was moved 5mm tangentially, in the ulnar direction at a speed of 5 mm/sec to induce full slip. The static coefficient of friction was measured at the onset of slip from the recorded normal force and tangential force values. All values in the manuscript refer to the static coefficient of friction.

III. RESULTS

A. Friction Modulation and Effect on Skin Contact

First, we evaluate the coefficient of friction values for the two frictional conditions. The mean coefficient of friction (μ) for the high and low friction condition was 0.48 ± 0.14 and 0.21 ± 0.10 respectively and the coefficient of friction of high friction was on average 2.2 times larger than the coefficient of friction of the low friction condition. Fig. 2 indicates the reciprocal of the coefficient of friction. A paired t-test indicated that the reciprocal of the μ was significantly different between the two friction conditions ($p = 0.0043$).

B. Effect of Contact Surface Displacement on Ability to Detect Frictional Differences

The effect of lateral movement distance was evaluated when the surface was moved laterally 0.2, 0.5, 1.2 and 2 mm in total, at a speed of 5 mm/s. When the contact surface was moved 2 mm relative to the finger, subjects were able to correctly identify which of two stimuli was slipperier in 90% (SD 12%) of trials (Fig. 3). Results were similar

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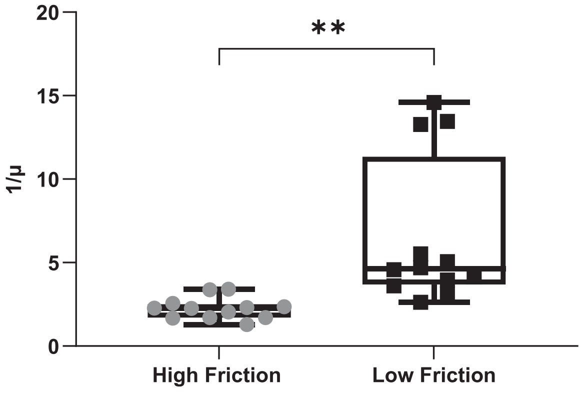

Fig. 2. Reciprocal of the static coefficient of friction measured for high and low friction conditions: Boxplots displaying the median and quartile range of quotient and means of the reciprocal of the coefficient of friction of the individual subjects. ** indicates $p = 0.0043$ (paired t-test).

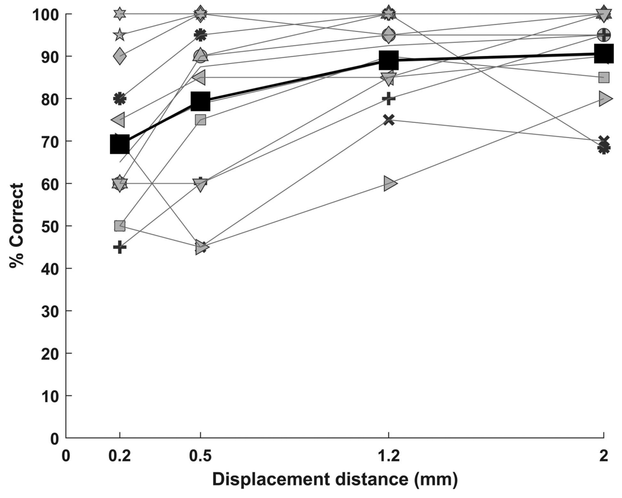

Fig. 3. Effect of displacement distance on ability to perceive frictional difference. Gray lines indicate individual subjects, and the solid black line indicates the mean percentage of trials in which subjects correctly identified the more slippery surface.

for a 1.2 mm surface movement (88% correct; SD 12%). Stimuli of 0.5 mm resulted in a slightly lower percentage of correct responses, with subjects on average correctly identifying the slipperier surface in 78% (SD 21%) of trials; and with 0.2 mm movements subjects on average responded correctly in 70% (SD 19%) of trials. Displacement magnitude influenced subjects' ability to detect frictional differences ($F(2.2, 25.2) = 8.6$, $p = 0.001$; one-way repeated measures ANOVA). There were significant differences between subjects $F(11,33) = 5.3$, $p < 0.0001$). The individual subject data points in Fig. 3 show that three subjects performed the discrimination task with very high accuracy (> 90%), two more performed above 75% reliably sensing frictional differences even with the smallest displacement of 0.2 mm.

We regarded the discrimination threshold to be 75% correct. Fig. 4 indicates the number of subjects (out of 12) who performed with greater than 75% accuracy at each displacement distance; and hence could discriminate between high and low friction. For example, five out of twelve subjects could perceive frictional difference with a plate displacement of only 0.2 mm.

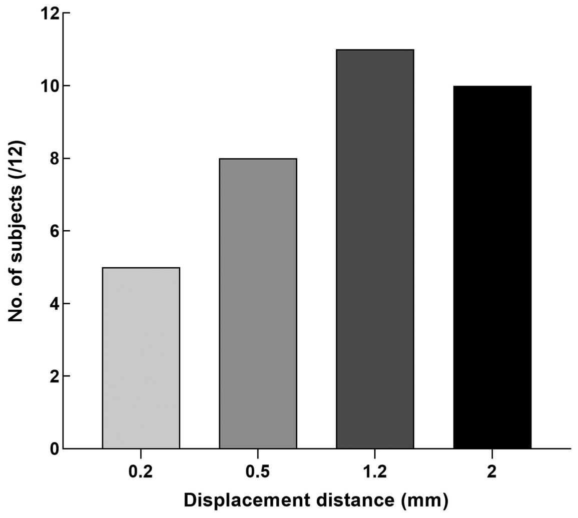

Fig. 4. Number of subjects who performed above criterion value (75%) at each plate displacement distance.

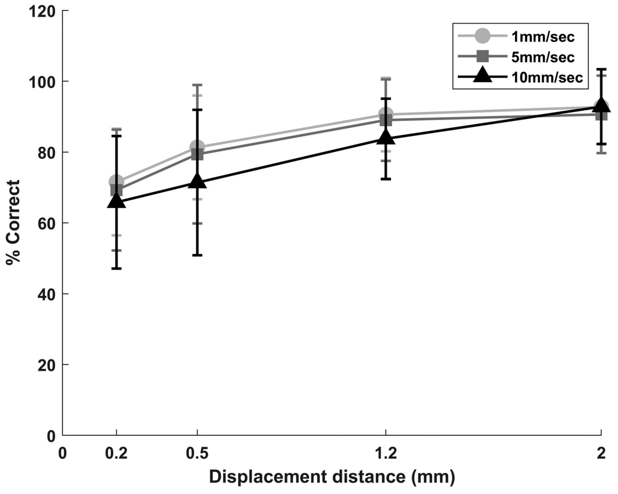

Fig. 5. Effect of displacement speed on subjects' ability to perceive frictional difference, with different displacement distances. The solid line connects the means of all the subjects across three different speeds and 4 lateral distances. The error bars indicate standard deviation across all subjects.

C. Effect of Displacement Speed on Frictional Difference Perception

In order to examine the effect of displacement speed on friction perception, we compared subjects' performance on three different speeds—1, 5, and 10mm/s—tested at each of the displacement distances. Fig. 5 displays means, and standard deviations of subjects' performances on the three displacement speeds, and 4 presented distances. The speed of plate displacement statistically had negligible effect on subject's performance ($F(1.654, 18.19) = 3.838$, $p = 0.0476$; two-way repeated measures ANOVA). Tukey's post-hoc analyses didn't identify differences between any of the speed pairs ($p > 0.05$). As the ten-fold increase in speed didn't cause a clearly observable effect on performance, we conclude that within the range tested the relative speed is not a critical parameter determining a human's ability to differentiate friction under such conditions.

D. Tangential Force Development due to Lateral Movement

The lateral movement of the surface generated tangential force which increased with the movement distance with both high and low friction surfaces (Fig. 6). This indicates that the maximum tangential force was not reached before at least 1.2 mm lateral displacement,

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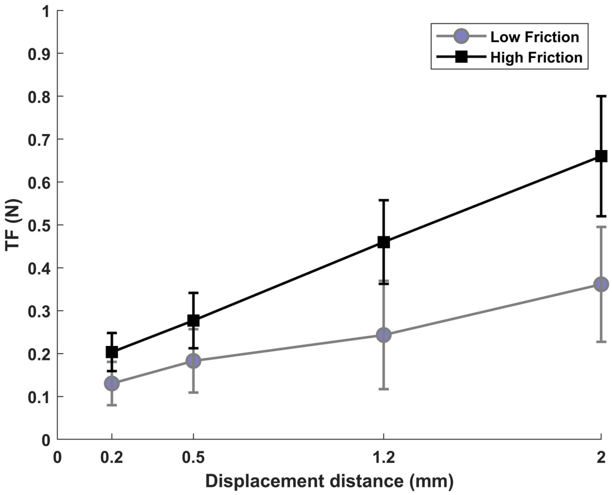

Fig. 6. Peak tangential force (TF) magnitude depending on displacement distance. The solid line connects the means of all the subjects at a lateral speed of 5 mm/sec. The error bars indicate standard deviations across all subjects.

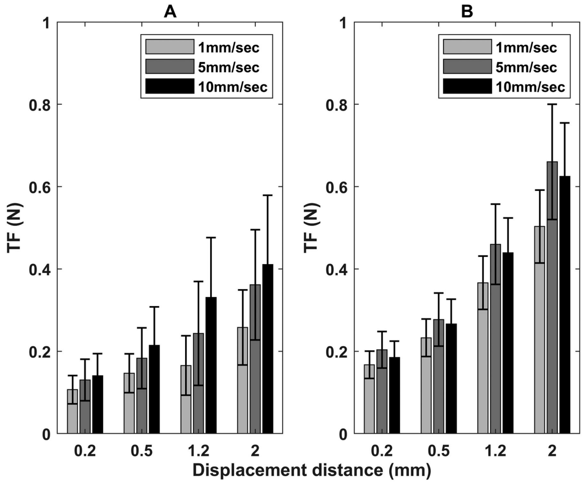

Fig. 7. The effect of lateral displacement speed on magnitude of peak tangential force. (a) Illustrates tangential force developed under low friction condition (b) Illustrates tangential force developed under high condition.

thus in a substantial number of trials full slips didn't occur. This means that partial slips within the contact area were sufficient to sense and raise awareness of slipperiness. The linear regression between displacement and tangential force magnitude revealed that two different slopes (0.36 vs 0.20 for high and low friction; $p < 0.01$; regression line forced through the origin). It is expected that the skin area pulled by the moving surface's frictional force (non-slipping portion) is smaller with slipperier surfaces, localized slips must have occurred to a larger extent. One interesting observation was that lateral movement speed influenced the magnitude of tangential force ($F(1.086, 11.94) = 45.52$ and $F(1.367,15.04) = 85.99$; $p < 0.0001$; Two-way repeated measures ANOVA (speed and distance as factors) for low and high frictional condition respectively). Post-hoc analyses identified significant effects of speed at all displacement distances with low friction surfaces—the faster the speed, the larger the peak tangential force (Fig. 7A). The effect was somehow different with the high friction surface – while the tangential force was larger with 5 mm/s speed than with 1 mm/s at every displacement distance ($p < 0.05$), the further increase in speed to 10 mm/s resulted in smaller tangential force than with 5 mm/s (Fig. 7B). This decrease was significant at three out of four tested displacement distances ($p < 0.01$) except 1.2 mm.

IV. DISCUSSION

The current study demonstrated that a lateral movement as small as 0.2 - 0.5 mm of the surface relative to the rigid nail-phalangeal bone complex is sufficient to perceive surface slipperiness. It shows that displacements that do not induce a full slip at the interface can be used to discriminate between frictional properties of two surfaces. Importantly, the finger was immobilized, so no movement related proprioceptive information could contribute, nor was active movement execution required to trigger perception [3]. The experiment was conducted using a smooth flat surface, thus no information about the displacement of surface texture elements was available, as it would be with a textured surface [1]. The most unexpected finding was that displacement speed changes, even by 10-fold, had relatively little effect. Judging by the force angle resulting from lateral movement, the full slip was not required to perceive the surface slipperiness. Below, we address how these findings compare with similar experiments reported in the literature and, based on available evidence, we speculate on possible sensory mechanisms involved.

A. Submillimeter Displacement Enables Discrimination of Friction

This study clearly demonstrated the role of minute lateral deformation of the skin in the perception of surface slipperiness. In particular, the exquisite sensitivity of touch facilitates the detection of partial slips, which are sufficient to perceive surface slipperiness. The results take on another dimension when considering the importance of friction estimation involved in grip force control mechanisms during object manipulation. Muscle activity during manipulation creates movement jitter in an order of magnitude comparable with the submillimeter deformation found here. Therefore, sensing the displacement and micro-slippage caused by the slipperiness could reveal the surface adhesive properties without requiring intentional exploratory movements. Such lateral movements contributing to friction sensing are expected to be part of natural movement patterns when holding and manipulating objects.

To apply these findings to motor control, one needs to be aware of the limitations. (i) When controlling grip force adjustments to friction, the motor control system may have access to richer sensory information than we perceive. In comparison, object slipperiness perception is important for motor control at the stage of motor planning but may not require such accuracy. For example, to prevent accidents, one would avoid making swift movements with a heavy tool if its handle is judged to be too slippery. (ii) Our experiments were performed with the finger immobilized in a well-controlled, constrained environment, which might have rendered more reliable cues for judgements in the 2-AFC task. The sensory signals might be more variable, and information more difficult to disentangle, under natural manipulation. Nevertheless, it is unlikely that subjects would exclusively base their decision only on some associated cues rather than their perceived sense of slipperiness, as they verbally indicated that they clearly felt surface slipperiness due to lateral movement.

In our previous study [1], subjects were unable to differentiate surfaces with comparable frictional differences to the current study, but without lateral movement, regardless of the surface texture (smooth, textured glass, or sandpaper). Surprisingly, the subjects were unable to feel frictional differences even when contact was made under a 20° angle, relative to normal, resulting in a force angle 8.9° and 2.5°

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in high and low frictional conditions, respectively, with a smooth surface. Such force angle was equivalent to the projected lateral displacement, which on average was still below 0.5 mm. An important difference is that in the current study lateral movement was made after the target normal force was reached, rather than making contact under the angle, thus resulting in considerably larger force angles and lateral forces. This can be explained by the skin being subjected to tensile strain starting from initial contact, causing parts of the skin to slip while the contact area is still small and gradually increasing. When contact is normal to the skin, slips due to lateral displacement will only be able to develop in more peripheral parts of the full-size contact area while larger parts will remain in safe contact and the underlying tissue will generate larger magnitude of tensile strain.

B. Sensing Frictional Differences: Contributions of Radial Divergence Patterns and Enhancements by Lateral Movement

Slip is required to evaluate friction between skin and a surface material. The shape of the fingertips and viscoelastic properties of the fingertip pulp allows partial slips to occur [4]–[8] without fully breaking contact with the surface. This is an important factor enabling friction sensing in the context of object manipulation. In fact, frictional differences could be sensed, and consciously perceived, when no lateral movement is made, based only on radial skin divergence patterns [9]. In that study subjects actively contacted the surface with a finger movement constrained in the orthogonal direction relative to the contact surface. Findings in the current study and by Willemet et al. [9] both agree and demonstrate that exploratory sliding movement and full slip are not required to perceive surface slipperiness. Thus, sensory conditions under which we perceive surface slipperiness are very similar to friction sensing used for grip force control during object manipulation, indicating that frictional information might be shared between motor and perceptual systems and rely on the same sensory input.

The differences between Willemet *et al.* [9] and the current study is that under our experimental conditions here the skin divergence pattern when making contact with a surface orthogonally wasn't enough to make judgements about slipperiness, and additional submillimeter range lateral movement was required. This could be explained by the fact that in Willemet et al. [9] subjects made active movements and, regardless of lateral movement constraint, were able to exploit the kinematics of contact by optimizing movement to enhance sensing of the primary cue available—the skin radial divergence pattern. In that study we noticed that, on average, subjects chose to use much higher normal forces (5.5 N), faster force rate (3.6 N/s), and movement was not constrained normal to the surface, so the development of net tangential forces is unavoidable due to mechanical anisotropies of the finger tissue and anatomical asymmetry. Thus, in the high friction condition with smooth glass the force angle on average was 9.9°. The subjects' performance was also influenced by the extent of frictional differences, which in the current study were smaller, but more likely to be encountered in ordinary daily tasks. All these factors might have contributed to optimization of sensory conditions and improved the ability to judge differences in slipperiness based on friction-dependent divergence patterns.

We interpret such variable subject performance under different circumstances, including passive and active conditions, to suggest that friction sensing is a very complex task reliant upon various interacting contributing factors. To make a reliable judgement, the nervous system uses various types of cues and sources of sensory information depending on availability [10]. For example, the higher the friction the more difficult it would be to differentiate between radial tensile strain (divergence) patterns, and this is where even a small lateral displacement (presumably slightly larger than with low friction) would have a highly important enabling role. In contrast, the radial skin divergence pattern might be more efficient to assess frictional differences with more slippery smooth surfaces when there is little tangential force developing and detection of the resulting lateral slip is difficult [11]. Overall, the divergence strain pattern is most efficient during the initial contact before considerable tangential forces develop to lift the object. When tangential forces increase there is a displacement between the rigid anatomical fingertip structures like bone and nail and the skin surface due to the soft fingertip tissue layers. This stimulates receptors within the contact area and especially around the nailbed, due to skin stretch and bulging at remote skin locations [12]. The extent of such lateral displacement (without involvement of a full slip) closely resembles experimental conditions in our current study and thus demonstrates that the tangential force development during lifting movements has a profound effect on the ability to sense and perceive frictional properties of the object's surface [13], [14]. Thus, we might become aware of object slipperiness immediately after contact is made under conditions characteristic of object manipulation.

C. Speed has Minor Effect on Perception of Slipperiness

One of the surprising findings in this study was that lateral movement speed had relatively little effect on surface slipperiness discrimination, even when displacement speed changed 10-fold. This indicates that sensory mechanisms used by subjects in the current study were unlikely to be primarily based on detection of vibrations caused by localized slips and stick-and-slip events determined by movement speed and associated acceleration profile and that the major contributor could have been a resulting skin deformation pattern. Detecting slips on smooth surfaces is difficult as there are no surface features indicating relative displacement and sliding, especially if static and dynamic coefficients of friction are very similar, so there is less probability to see stick-and-slip events [10]. Thus, the pattern of tensile and compressive strain is the best candidate to be the major factor contributing to subjects' perception of slipperiness in the current study. This is well supported by evidence obtained in virtual haptic environments where skin stretch increases the perception of virtual friction [15].

D. Sensory Mechanisms

Microneurography recordings and population modeling have demonstrated that tactile afferent populations have significant capacity to encode frictional differences at the initial contact with surfaces, even in the absence of tangential forces [16]. This is expected as empirical evidence based on fingerprint deformation image analyses and mechanical modeling of radial tensile strain clearly demonstrate significant frictional effects. Nevertheless, afferent performance does not necessarily result in the human ability to perceive those differences [17]. Some of the possible explanations are discussed in [1].

It is not enough to obtain frictional information only at the initial touch. The coefficient of friction between the skin and surface are under continuous change due to various factors discussed in detail in [14]. During object manipulation, submillimeter range lateral skin stretch is typically present even with very moderate load forces. Our findings indicate that such lateral skin stretch may play a crucial role in increasing the richness of sensory information available about friction. When gripping and lifting an object the initial grip force adjustment may not be sufficient and detection of incipient slip would prevent an object slipping and falling out of the grip. The information

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about incipient slip would serve as a command to tighten the grip. Indeed, it has been demonstrated at the level of single human afferents that sensory information is available to warn of incipient slip [18], [19]. Afferent population modeling has revealed that tactile afferents are capable of providing quantitative high precision information about the remaining load-bearing capacity of the grasp, i.e., with better than 10% precision even a small number of afferents are enough to inform the motor control system about the current fraction of tangential force relative to the slip force and thus how much tangential force is permitted to increase before contact would be lost [20].

V. CONCLUSION

Submillimeter range lateral displacement of the fingertip relative to the surface is sufficient to perceive surface slipperiness. It is important that such movement is not associated with full slips of the same magnitude, so that frictional forces maintain adhesion between the surface and skin. We conclude that the consequences of partial slips within the contact surface and fingertip tissue deformation create very potent sensory stimuli, enabling tactile afferents to signal friction-dependent mechanical effects resulting in surface slipperiness perception. These quantitative data have significant value for designing haptic devices that render slipperiness on tactile displays and in virtual environments.

From the motor control point of view, natural movements when reaching and gripping objects would rarely occur without the presence of subtle lateral motion jitter. Our findings indicate that such movements are sufficient and potentially could be the key enabling us to feel slipperiness of the surface.

Unlike sliding and rubbing fingertip movements used for surface exploration, sensory conditions under which subjects discriminated surface slipperiness in the current study were more similar to friction sensing used for grip force control during object manipulation indicating that frictional information might be shared between motor and perceptual systems and rely on the same sensory input.

In summary, the findings of this study significantly extend our understanding of fundamental tactile sensory processes involved in perception, but also has relevance for the motor control strategies associated with dexterous object manipulation tasks. This knowledge will assist design of haptic rendering devices. This study has implications in the fields of haptics and extends the understanding of tactile sensorimotor control strategies required for dexterous object manipulation.

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