Effect of skin hydration on the dynamics of fingertip gripping contact

T. André¹,², V. Lévesque³, V. Hayward⁴, P. Lefèvre¹,² and J.-L. Thonnard¹,*

¹Institute of Neuroscience (IoNS), Université catholique de Louvain, Brussels, Belgium
²Institute of Information and Communication Technologies, Electronics and Applied Mathematics (ICTEAM), Université catholique de Louvain, Louvain-la-Neuve, Belgium
³Department of Computer Science, University of British Columbia, Vancouver, Canada
⁴UPMC Univ Paris 06, Institut des Systèmes Intelligents et de Robotique, 75005 Paris, France

The dynamics of fingertip contact manifest themselves in the complex skin movements observed during the transition from a stuck state to a fully developed slip. While investigating this transition, we found that it depended on skin hydration. To quantify this dependency, we asked subjects to slide their index fingertip on a glass surface while keeping the normal component of the interaction force constant with the help of visual feedback. Skin deformation inside the contact region was imaged with an optical apparatus that allowed us to quantify the relative sizes of the slipping and sticking regions. The ratio of the stuck skin area to the total contact area decreased linearly from 1 to 0 when the tangential force component increased from 0 to a maximum. The slope of this relationship was inversely correlated to the normal force component. The skin hydration level dramatically affected the dynamics of the contact encapsulated in the course of evolution from sticking to slipping. The specific effect was to reduce the tendency of a contact to slip, regardless of the variations of the coefficient of friction. Since grips were more unstable under dry skin conditions, our results suggest that the nervous system responds to dry skin by exaggerated grip forces that cannot be simply explained by a change in the coefficient of friction.

Keywords: skin hydration; biomechanics; biotribology; haptic; touch

1. INTRODUCTION

Human haptic behaviour depends critically on the efficient integration of afferent tactile signals. Such signals are produced by thousands of mechanoreceptors that innervate the glabrous skin and are stimulated by skin deformation [1–5]. These signals enable the central nervous system (CNS) to be aware of the properties of a touched surface, allowing the CNS to adapt its motor strategy to the intended task. See Augurelle et al. [6] and Witney et al. [7] for recent surveys. When holding an object, the normal component of the grip force must be sufficient to prevent slip [3]. The smallest grip force providing a stable grasp depends on the properties of the gripped object, including its mass, geometry, material and surface finish. Humans rely on tactile afference to adjust the grip force in accordance with such object properties [8–10]. Frictional properties and grip stability, however, also depend on skin hydration as much as they depend on the object itself [11].

Here, we experimentally investigated the details of the mechanical events occurring during the transition period between an entirely stuck contact and a fully developed slip, and the dependency of these events on skin hydration. When performing a dynamic gripping task, external loading initially deforms the skin; when slip occurs, it does so first at the periphery of the contact region according to a classic result in contact mechanics ([12], ch. 7). The time course of the strain distribution in objects in unilateral contacts that evolve from a stuck state to slip is termed ‘contact dynamics’ and is a branch of study of general contact mechanics. This phenomenon can be readily observed in finger slips [3,13]. The contact dynamics during the transition stage may inform the nervous system of a corrective behaviour to adopt to maintain grip stability. These transitional events, however, have not yet been directly quantified.

While many authors have considered models of finger deformation under strictly normal finger loading [14–22], composite loads that include significant tangential components are particularly relevant in the investigation of grip behaviour. Few studies have evaluated the lumped biomechanical behaviour of the fingertip. Nakazawa et al. [23] characterized the lumped stiffness and viscosity of the human fingertip under tangential isometric loading, and Pataky et al. [24] studied bulk relaxation after quasi-static loading. The micromechanical
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2. METHODS

2.1. Materials

2.1.1. Optical system. We used an optical fingerprint recording technique based on the principle of frustrated total internal reflection. The apparatus included an intense diffuse light source, right-angle prism and camera (figure 2a). Light propagated towards the 45° face of the prism where the fingertip was in contact. When there was no contact, light was totally reflected towards the camera, creating a bright, uniform image. When the fingerprint ridges were in contact with the prism, total internal reflection was frustrated, resulting in a high-contrast pattern of black ridges on a white background.

The optical system, originally developed by Levesque & Hayward [26], used a 250 W halogen lamp as the light source and a right-angle prism (50°/C2 70 mm) made of BK7 glass. A monochrome, progressive scan CCD camera (TM-6703, Pulnix America, Inc., Sunnyvale, CA, USA) recorded the reflected images with a 8-bit camera (TM-6703, Pulnix America, Inc., Sunnyvale, CA, USA) connected to a personal computer. Images were acquired in a streaming mode by a frame grabber (Meteor-II/Multi-Channel, Matrox Electronic Systems Ltd., Dorval, Canada) connected to a personal computer. Images were processed using Matrox Imaging Library v. 6.1. An electronic signal generated by the frame grabber at the onset of video recording allowed synchronization with force measurements. Zoom magnification was adjusted for each subject and each normal force so that measurement resolution was maximized according to the contact surface size. After each adjustment, the system was optically calibrated using a reticle having a grid of dots 1 mm apart. The smallest measurement resolution was 20 pixels mm⁻¹ in all cases.
2.1.2. Mechanical system. The prism was rigidly mounted on a force/torque sensor (Mini40 F/T Transducer; ATI Industrial Automation, NC, USA) that measured the forces and torques by the subject (figure 2c,d). This set-up allowed us to determine the three components of the interaction force, \( F_x \), \( F_y \) and \( F_z \), in the ranges of \( \pm 40 \), \( \pm 40 \) and \( \pm 120 \) N, respectively, with 0.01, 0.01 and 0.02 N resolution, respectively.

2.1.3. Skin hydration measurement. Skin hydration was measured with a Corneometer CM825, which operates using a capacitance principle. The probe comprises a 7 mm square ceramic tile with many closely spaced gold electrodes that act as capacitor plates. Electrodes are protected by a 20 \( \mu \)m thick vitrified dielectric material. Measurements are given in arbitrary units ranging from 20 (very dry) to 120 (very moist). The Corneometer is fully described in Fluhr et al. [34,35].

2.2. Experimental procedure

Ten healthy Caucasian subjects (from 20 to 30 years of age) participated in this study. Fifteen minutes before the experiment, subjects washed their hands with soap and water and the experimenter verified that their hands were rinsed and dried carefully. All subjects provided informed consent, and the experimental protocol was approved by the local ethics committee. Subjects were seated in front of the experimental set-up and were instructed to apply a constant normal force on the imaged face of the prism with their right index fingertip. Visual feedback provided them with the normal force component actually exerted. The experimenter checked visually that the initial angle between the glass surface and their distal phalange was within 20–30°. When the normal force was stabilized at a given level (specified by the experimenter), subjects performed an ulno-radial tangential slip (vertical arrow, figure 2c). The fingertip skin moisture was measured before and after each trial. Each subject performed five trials for six levels of normal force: 0.2, 0.5, 1, 2, 5 and 10 N. Subjects easily maintained a nearly constant normal force component. Its value did not vary by more than \( \pm 10 \) per cent during the task.

2.3. Data processing and variables studied

The force transducer signals and the trigger signal from the CCD camera were acquired with a 12-bit 6071E
analogue-to-digital converter in a PXI chassis (National Instruments, Austin, TX, USA). The trigger signal allowed synchronization of the video frames with the force recordings. Force signals were low-pass-filtered with a fourth-order, zero phase-lag Butterworth filter, which has a cut-off frequency of 10 Hz. Statistical analyses were performed using SAS software.

2.3.1. Image processing. Optical flow is a technique commonly used in computer vision. This technique allows the estimation of a displacement vector for each pixel of the original image, and the registration of the two images into the same coordinate system. The simplest implementation involves overlaying two or more frames taken at different instants in time [36]. We compared each selected frame of the fingertip surface of contact (Im(t2), figure 3) with the previous frame (Im(t1), figure 3). The displacement vector was coded using a grey scale, where black indicated a null displacement and white indicated a displacement of 20 pixels.

The optical flow computation revealed a contact region represented by a grey region on a black background, and a stuck region was represented by a black region within a grey region (figure 3). Inside the contact region, the grey levels indicated the displacement gradient.

The Lucas–Kanade method [37] was used to quantify displacement. Given images F1(x) at time t1 and F2(x) at time t2, we sought vector h, such that

\[ h \approx \sum_x \left( \frac{\partial F_1}{\partial x} \right)^T [F_2(x) - F_1(x)] \times \sum_x \left( \frac{\partial F_1}{\partial x} \right)^T \left( \frac{\partial F_1}{\partial y} \right)^T, \]

where

\[ \frac{\partial}{\partial x} = \left[ \frac{\partial}{\partial x} \frac{\partial}{\partial y} \right]^T \]

in two-dimensional images. While vector h corresponds to the global displacement between two images, the displacement can also be estimated for any portion of an image.

2.3.2. Fitting ellipses. Further characterization of the different regions was done by fitting an ellipse at the outer border of each region. This procedure provided spatial filtering that attenuated measurement noise. It also had the benefit to furnish a notion of shape for the surfaces of interest. The experimenter selected at least 10 points at the border of the region to be quantified. The best-fitting ellipse was found using a least-squares criterion that minimized the sum of the distances between the 10 points and the curve (figure 3, ellipse fitting). Considering the ellipse equation:

\[ ax^2 + bxy + cy^2 + dx + ey + f = 0, \]

and letting \( p = (a, b, c, d, e) \) be the vector of parameters to be estimated normalized to \( f \), then

\[ P = \sum(X) \frac{X^T X}{X^T X}, \]

where \( X \) is a matrix of the form \((x^2, xy, y^2, x, y)^T\) of all the measurement vectors \((x, y)^T\). We used this procedure to estimate the areas of the total and stuck contact regions.

The areas estimated with this method never differed by more than 4 per cent from the areas estimated by the time-consuming procedure of direct counting of the pixels (criterion validated on ten samples).

3. RESULTS

The temporal evolutions of the normal (NF) and tangential (TF) components of the interaction force for a typical trial are shown in figure 4 (top). When NF applied to the prism by the index finger was stabilized around the target value, subjects ramped up TF during the preloading period (figure 4, grey area) until slip fully occurred. At this point, the frictional force balanced TF and the magnitude of TF plateaued (figure 4, black arrow). During the preloading and slipping phases, a subset of frames separated by 150 ms intervals was selected to compute ‘optical flow images’ (figure 4, bottom; see §2.3.1). Four of these frames are exemplified in figure 4 (middle). Each of these frames was then associated to the normal and tangential force components, TF and NF, respectively (figure 4, dashed lines and white dots). The area of the contact region varied a little during the tangential loading...
subject TA at a constant NF of 5 N is shown in figure 5 at high values. Changes in NF at low values only, and was saturated at 0.2 N. Thus, the contact area was sensitive to contact area at 10 N was three times larger than that face was nearly 80 per cent of its final value, and the maximal value asymptotically. At 2 N, the contact surface decreased when the tangential force component increased. The normalized contact area increased but reached a steady slip, there was very little variation in the contact area for each subject and for a 10 N normal force varied from 177 to 288 mm$^2$ (table 1). To compare the results between subjects, the contact region areas were normalized to the largest contact area attained when NF was 10 N. Figure 5 shows the relationship between NF and the normalized contact area when TF was zero. The normalized contact area increased but reached a maximal value asymptotically. At 2 N, the contact surface was nearly 80 per cent of its final value, and the contact area at 10 N was three times larger than that at 0.2 N. Thus, the contact area was sensitive to changes in NF at low values only, and was saturated at high values.

A typical time course of the normalized contact area for subject TA at a constant NF of 5 N is shown in figure 5 (black dots). The normalized contact area decreased moderately over time until it reached a constant value, which corresponded to the normalized contact during full slip. Because of the initial deformation of the tissues, the contact area diminished during the preloading period (grey area in figure 4). This effect translated into an average of 12.5 per cent shortening of the ellipse A-axis. During steady slip, there was very little variation in the contact area.

### 3.1 Static characteristics of the contact area

The areas of the total contact region and stuck region were estimated for each optical flow image. The subjects had large anatomical differences, as the contact areas for each subject and for a 10 N normal force varied from 177 to 288 mm$^2$ (table 1). To compare the results between subjects, the contact region areas were normalized to the largest contact area attained when NF was 10 N. Figure 5 shows the relationship between NF and the normalized contact area when TF was zero. The normalized contact area increased but reached a maximal value asymptotically. At 2 N, the contact surface was nearly 80 per cent of its final value, and the contact area at 10 N was three times larger than that at 0.2 N. Thus, the contact area was sensitive to changes in NF at low values only, and was saturated at high values.

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### 3.3 Effect of hydration

The effect of skin hydration on the finger contact dynamics can also be evaluated by comparing the relative increase in TF before slippage. Figure 6 shows with black squares the TF magnitudes for an SR of 0.5. Hydration levels could then be associated to the TF during full slip, i.e. SR = 0 (figure 6a, black circles). The ratio between the tangential force component, TF and its ultimate value, TFslip, can be viewed as a
measure of the ‘sensitivity’ of a contact to perturbations. A ‘robust’ grip has a low sensitivity.

Figure 7 illustrates the effect of hydration on the quantity $\frac{TF}{TF_{slip}}$ at a specific point of a developing slip ($SR = 0.5$). The data are from the two subjects who exhibited the largest hydration variation for all NF values combined with a significant decrease of the ratio $\frac{TF}{TF_{slip}}$ when hydration increased ($p < 0.0051$, Bonferonni-corrected). The other subjects had an individual hydration variation below 30 arb. units. Figure 8 summarizes the data of all subjects and all NF values. Figure 8a shows the effect of hydration on the value of $\frac{TF}{TF_{slip}}$ for each subject for the same slip ratio value, $SR = 0.5$. Figure 8b shows the effect of hydration on the value of $\frac{TF}{TF_{slip}}$ at different phases of a developing slip ($SR = 0.25$, 0.5 and 0.75). On average, the ratio $\frac{TF}{TF_{slip}}$ increased as the slip ratio, $SR$, decreased, that is, the sensitivity of the contact decreased when it was closer to full slip. The quantity $\frac{TF}{TF_{slip}}$ also decreased with hydration for all three $SR$ values. In other words, dry skin always corresponded to grips that were more sensitive to disturbances. The variations of $\frac{TF}{TF_{slip}}$ could be represented by a linear mixed model that used hydration as a fixed effect and the subject as a random effect (SAS software). This method allowed us to study the interaction effect between hydration and subject (hydration × subject). The results showed that hydration had a significant effect ($p < 0.001$) which was not the case of that of hydration × subject.
interaction \((p = 0.9706)\), confirming that the effect illustrated by figure 8 is linked to hydration. The subject effect was also significant \((p < 0.001)\). For a dry skin, when the contact is half slipping \((SR = 0.5)\), the ratio \(TF/TF_{slip}\) is close to 0.9, that is, the transition to full slip is imminent. In contrast, for a higher level of hydration, this ratio can reach 0.6 for the same contact condition. Thus, when hydration is low, a 10 per cent disturbance in tangential loading can provoke slip, whereas a 40 per cent increase is needed to achieve the same result in well-hydrated skin. At any point of a developing slip, the higher the skin hydration is, the further the skin is from the full slip. This observation holds true regardless of the NF value.

4. DISCUSSION

Previous studies investigated the effects of skin hydration on the global characteristics of a finger contact \([30, 38-40]\). The present study showed that skin hydration impacts finger contact dynamics as expressed by skin surface deformation under tangential loading. The effects of skin hydration were imaged directly and we could observe how the contact transition from adhesion to slip varied as a function of skin hydration. To quantify this effect, we first evaluated the skin area undergoing slip relative to the total contact region. We observed that the tangential force component \(TF\) reached a maximum when the entire contact surface slipped. More significantly, skin hydration strongly impacted the relative increment of tangential loading available before a complete slip developed, regardless of the normal force component \(NF\) and regardless of the contact state. In all cases, the greater the skin hydration magnitude was, the further the contact was from slipping.

4.1. The notion of incipient slip

Johansson & Westling \([3]\) described the importance of the cutaneous sensory feedback in precision grips. They showed that the nervous system adapts the grip force as a function of object friction properties. They hypothesized that continuous tactile feedback arises from partial slips, termed ‘incipient slip’, occurring at the periphery of the contact region. However, few studies have quantified this effect. Tada \textit{et al.} \([13]\) introduced the SR to quantify the contact state, and presented experimental data that were similar to ours: the SR decreased linearly when tangential loading increased. However, these authors tested proximo-distal finger movements with normal force components \(\leq 1.5\, N\), and did not investigate the role of skin hydration. In the present study, we used ulno-radial movements that are
more relevant to gripping behaviours, a much larger force range from 1 N to 5 N, and measured skin hydration. These factors are all significant to dextrous manipulation.

Incipient slips are widely used in robotics to develop robots that can dynamically adapt the grasp force to object properties [41–44]. Tremblay & Cutkosky [44] made a robotic finger that had an artificial skin covered with ‘nibs’ that formed local contact regions and could slip independently. When partial slip occurred, some ‘nibs’ located peripherally emitted a vibration that was used to adapt the gripping force. Maeno et al. [42] described an artificial skin with strain gauges bonded to phosphor bronze plates embedded in silicon rubber. Incipient slip was detected from the relative displacement of each plate. They showed that broad contact conditions (non-contact, slip or stick) varied with the normal and tangential force components. Recently, Edin et al. [41] developed an artificial tactile system with miniature strain gauges embedded in a bio-mechatronic hand that provides rich information during manipulation tasks, including slip information between the fingertip and an object.

4.2. The effect of hydration

For equivalent contact states (encoded by SR), we found that the contact safety margin increased when skin hydration increased (at least when touching a glass surface), regardless of the normal loading. This result contributes to our understanding of motor behaviour when grasping or manipulating objects. Smith et al. [45] observed that people who were administered scopolamine spontaneously employ higher grip forces. Scopolamine reduces skin hydration through reduced sweat gland activity, which in turn modifies the finger/object frictional interaction. Recently, we demonstrated a causal relationship between skin hydration and grip force [11]. Subjects with a dry skin spontaneously employed a greater grip force at a level that is not compatible with a simple compensation for the reduction of friction: a 40 per cent of friction reduction was associated with a 140 per cent increase of grip force. The minimal grip force required to prevent the object from slipping directly depends on the finger-object friction but the excess of grip force is also related to other factors like cognitive or environmental factors. In the light of the present results, we can speculate that the CNS behaves in such a manner that when the skin is dry, the gripping force is commanded to be exaggeratedly large to reduce the effects of disturbances. Seen from the view point of the time course of the motor commands needed to produce a stable grip, dry skin reduces the ‘time-to-slip’, making the grip potentially even less robust against unknown factors. The quantity TF/TFSlip is analogous to the notion of the ratio of required friction to available friction that was employed in the study of Hanson et al. [46]. Interestingly, our results are also related to the findings of Gerhardt et al. [47], who reported to have found a linear relationship between skin hydration and skin friction. The linear decrease of the ratio TF/TFSlip as a function of hydration observed in the present study could be owing to this relationship.

4.3. Tribology of finger contact and possible mechanisms

The tribology of finger skin adhering or sliding on surfaces is a complex phenomenon resulting from the interplay of several physical effects, including water-mediated capillary adhesion, plasticization of stratum corneum, ridge squashing, elastohydrodynamic lubrication and modulation of water migration as a function to the porosity of the surface in contact with the finger. All of these effects depend critically on the hydrophilic properties of the tissues of the fingertip as well as on the mechanisms of sweat secretion and re-absorption [28]. The combination of these effects points to a critical role of water above and beyond the modification of the frictional properties of the skin per se, having an impact on the dynamics of transition from adhesion to slip.

It is possible to speculate on the mechanisms contributing to the global effect we observed. There are at least three distinct yet related phenomena. First, moist skin is more flexible than dry skin [28]. As a result, the bulk dynamics of deformation are faster with dry skin, making it harder for the nervous system to sense them for corrective action. Second, hydration could have mechanical consequences at the scale of the ridges. Glabrous skin ridges determine the ‘effective contact area’ inside a contact region [48]. A moist, softer skin could reasonably provide a larger effective contact area than dry skin for the same contact region, increasing the net friction [49]. Third, the superficial, keratin-based, fibrous skin layers present strong affinity for endogenous or exogenous water, modifying the skin mechanical behaviour at the microscopic scale. Interfacial microscopic stress distributions are probably strongly dependent on the presence or absence of water, especially during interactions with smooth surfaces [50].

4.4. Perspectives

The experiment presented here was performed using active touch. Subjects exerted a force with their index finger and used visual feedback to regulate the normal component. They performed the task adequately, leading to a standard deviation of the normal component that was smaller than 20 per cent of the mean, even during the preloading phase. The spontaneous preloading period was nearly constant (approx. 700 ms) suggesting another type of compensating motor behaviour. To control these factors, in future studies, the subjects’ fingers should be stimulated by a servo-controlled apparatus where all the mechanical variables could be regulated independently, including the servo-controlled apparatus.

4.5. Conclusion

Skin hydration modifies the skin deformation dynamics during grip-like contacts. Certain motor behaviours observed during object manipulation could be explained by the effects of skin hydration. We suggest that the overcompensation strategy seen when the skin is dry...
could be explained by important variations in the contact dynamics as a function of skin hydration.

Our results, so far, are specific to glass surfaces that are perfectly smooth and stiff in the range of forces considered. The fact that glassy surfaces are not porous and confine water at the interfaces is likely to contribute to the effect that we have observed. With other contact imaging modalities, similar experiments could be conducted with surfaces such as wood or plastic. We expect that the qualitative aspects of our study would extend to these cases as well.

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