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A continuous measure of fingertip friction during precision grip

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ABSTRACT

When humans manipulate an object, the minimal grip force (GF) required to avoid slipping depends on the frictional properties between the fingers and the object. As a consequence, fingertip skin friction plays a critical role during object manipulation. Here, the effects of the normal force and moisture content on the skin's static coefficient of friction (CF) for human fingertips were studied. Ten subjects were asked to pinch an object with a given normal force. Slippage of the object on the fingertips was generated for different ranges of normal force using a linear translation stage. The exerted forces and moisture of the fingertips were then measured, and the static coefficient of friction was calculated as the ratio between the tangential force and normal force at slippage. These results demonstrate that the effects of the normal force and moisture content on the CF exhibit a complex interaction. For a given moisture condition, the CF varies as a power function of the normal force; in contrast, for a given normal force, the CF is described by a "bell-shaped" function of moisture. A global expression of the CF as a function of the normal force and moisture content is derived, and a method is proposed for a continuous measure of the CF. This new method shall be of particular interest in investigating dexterous manipulation.

1. Introduction

Precision grip allows humans to manipulate small and/or delicate objects. In this grip configuration, the object is held between the thumb and index finger. The grasp stability is ensured by a close coordination of the forces exerted on the object by the tips of the fingers: the grip force (GF) applied normal to the object's surface must be sufficient to counteract both the gravitational and inertial components of the tangential load force (LF) (Johansson and Westling, 1984). During tasks of precision manipulation, the grip force must be well adapted with load force variations in order to avoid slipping of the object (Flanagan and Tresilian, 1994) but also to avoid damaging the object or muscle fatigue. Moreover, it has been shown that adjustments of the normal grip force anticipate tangential load force changes, provided that the physical properties of the object are predictable (Flanagan and Wing, 1993, 1995). Several studies (Westling and Johansson, 1984; Flanagan et al., 1995; Cadoret and Smith, 1996) have pointed out that the static coefficient of friction (CF), as well as the weight and the grip configuration (McDonnell et al., 2005), are primary factors when studying object manipulation. Indeed, the minimal grip force required for the object not to slip is key to understanding human performance and is directly related to the CF (Westling and Johansson, 1984).

The static coefficient of friction is defined as the ratio between the tangential force and normal force when slipping first occurs (Bowden and Tabor, 1982; Blau, 2001). Earlier studies found that the force of friction was directly proportional to the applied load and was independent of the contact surface. This is known as Amontons' law, indicating that the CF is a constant for two given surfaces. However, Comaish and Bottoms (1971) showed that this law does not hold for the skin and, more specifically, for low values of the normal force (<3.5 N). This study demonstrated a relationship for the CF between the skin and a probe that closely follows a negative power function and depends upon the applied normal force. Several subsequent studies have further characterized this relationship (Wolfram, 1983; Koudine et al., 2000; Sivamani et al., 2003) for different body parts, such as the forearm or dorsal side of the finger.

Moisture is another factor that influences the CF between the skin and object. The effect of water on the skin has already been described in several studies (Comaish and Bottoms, 1971; Buchholz et al., 1988; Adams et al., 2007). In particular, Adams et al. (2007) observed that the skin's friction actually increases in the presence of water and decreases during the subsequent drying period. Derler et al. (2007) quantified the moisture content of the skin with a commercial device named the Corneometer (Fluhr et al., 2000) and studied the dependence of the friction coefficient on the applied normal load for moist and dry skin. They found a strong increase in CF with moisture and suggested that further investigations with human subjects were needed to study the influence of skin hydra-

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tion on friction in detail. Indeed, none of these previous studies precisely and continuously quantified the moisture of the skin with an adequate sensory probe. Moreover, when manipulating objects, an occlusion occurs at the finger/object interface. As a consequence, the moisture content and thus the CF vary during the task (Fluhr et al., 2000). It is therefore crucial to measure the moisture of the skin continuously during manipulation tasks in order to better understand the role of the CF in grip force control.

Different techniques have been used in the past to estimate the static coefficient of friction (Turrell et al., 2001). The most widespread approach in dexterous manipulation involved asking subjects to slowly separate the thumb and index finger until an object dropped. Using the ratio of the TF/NF when slipping was initiated, the CF could be estimated. As a consequence, this technique implied to evaluate CF before and/or after performing an object manipulation task. However, CF varies over time during object manipulation. In the present paper, we studied two variables that influence CF and we provide a method to measure CF continuously during a precision grip task. The influence of both the normal force and moisture content on the static coefficient of friction between the skin and object surface suggests that both of these factors must be taken into account when studying the CF. Indeed, the normal force and moisture content vary during a dexterous manipulation; consequently, the CF must vary as well. The CF between the fingertip and object should not be evaluated *a priori* but instead continuously estimated by considering the varying normal force and moisture. This paper studies the combined effects of both factors on the CF, and we obtain a global relationship between these three variables. A general analytical expression of the CF that depends on both the normal force and moisture content is reported, and this expression is used to propose an original method for a continuous estimation of the CF during precision grip.

2. Materials and methods

Ten healthy Caucasian subjects (five women and five men) participated in this study. Their ages ranged from 20 to 53 years. All subjects provided informed consent, and the experimental protocol was approved by the local ethics committee.

2.1. Apparatus

The mechanical system used in the experiment is illustrated in Fig. 1. A linear translation stage (NLS4 Series Precision Linear Stage, 6" Travel, Newmark System Inc, CA, USA) controlled the displacement of a base, which in turn compressed two springs. The compression generated a vertical force on an object held in a precision grip by the participants. This object included two force/torque transducers (Mini40 F/T transducer; ATI Industrial Automation, NC, USA) and two moisture sensor probes. Each force/torque transducer measured the normal (NF, *z*-axis) and tangential force (TF, *y*-axis) at the interface with the thumb or index finger. The sensing ranges for the TF and NF were ±40 N and ±120 N with 0.01 N and 0.02 N nominal resolutions, respectively. The torques and forces measured by the sensors were used to determine the center of pressure at the fingertip:

$$\mathrm{CP} = \frac{T}{\mathrm{NF}}$$

where CP, *T*, and NF correspond to the center of pressure, torque, and normal force, respectively. CP corresponds to the coordinates of the point at which the resultant NF should be applied to generate the measured torque (*T*). The mechanical configuration of the setup (see Fig. 1) allows only vertical movements of the mobile stage. As a consequence, only the *y*-component of CP is reported in the data. The vertical mobile stage speed was 1 mm/s.

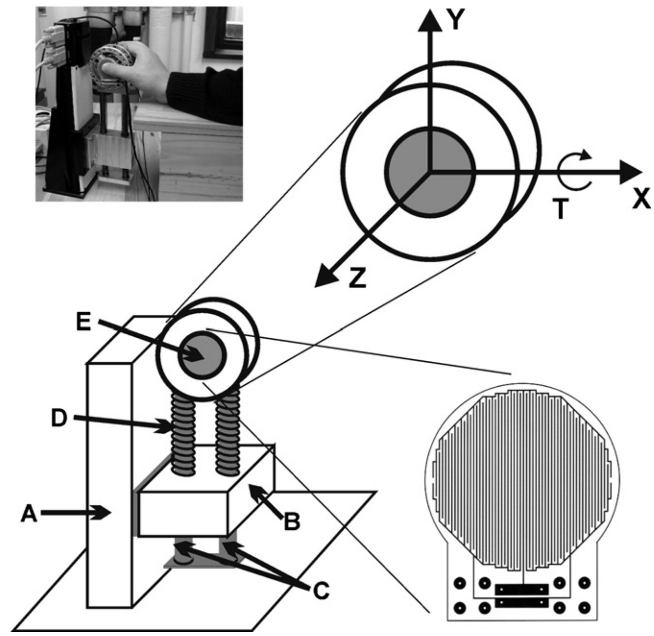

Fig. 1. A linear translation stage (A) was fixed on a table and controlled the displacement of a base (B), which was connected to its mobile stage. Two axes (C), not linked to the base, were surrounded by springs (D) and connected to the instrumented object (E). The latter was composed of two force/torque sensors (reference frame on the right-top part of the figure) on which probes of a moisture sensor (inset on the right-bottom part of the figure) were glued. When the object was kept immobile by the subject, any vertical upward displacement of the mobile stage led to a movement of the base that then compressed the springs and generated a vertical force on the instrumented object.

Skin hydration at the fingertip was measured with moisture sensors (Moisture Evaluator; André et al. (2008)). This task-dedicated device used the conductance principle to evaluate moisture content and provide a reliable, quantitative measure of skin hydration during the task. It consisted of an adapted probe composed of 56 gold-covered electrodes (see inset on right-bottom part in Fig. 1) fixed on a Bakelite support and an electronic circuit to evaluate skin conductance. The numerical scale of the probe ranges from 4 to 10 in arbitrary units (a.u.), representing very dry to very wet skin, respectively. It is worth mentioning that the normal force exerted on the probe does not affect significantly the Moisture Evaluator reading (effect < 5% within 0.2 N with 2 N range, André et al. (2008)). For our quantitative analysis, an ordinary scale covering the whole range of moisture was arbitrarily defined and separated into four categories as follows: dry: 4–5.5 a.u.; normal: 5.5–7 a.u.; wet: 7–8.5 a.u.; very wet: 8.5–10 a.u. It is important to note that no additional water was applied at fingertip to obtain the very wet state. This classification was subject-independent. According to subjects' actual skin hydration at the time of the experiment, it permitted several subjects to cover more than one range of moisture. These intra-subject moisture variations allowed us to check that each individual subject followed the general tendency with respect to his/her own skin hydration.

2.2. Experimental procedure

Subjects were seated comfortably with a horizontal support under their forearm and wrist. They were asked to pinch the object (item E in Fig. 1) between the thumb and index finger. Visual feedback of the NF was provided to the subject, allowing him or her to exert different levels of force on the object according to our instructions. The experiment consisted of producing slippage between the fingers and object for different levels of NF. The linear translation stage (Koudine et al., 2000; Adams et al., 2007) generated

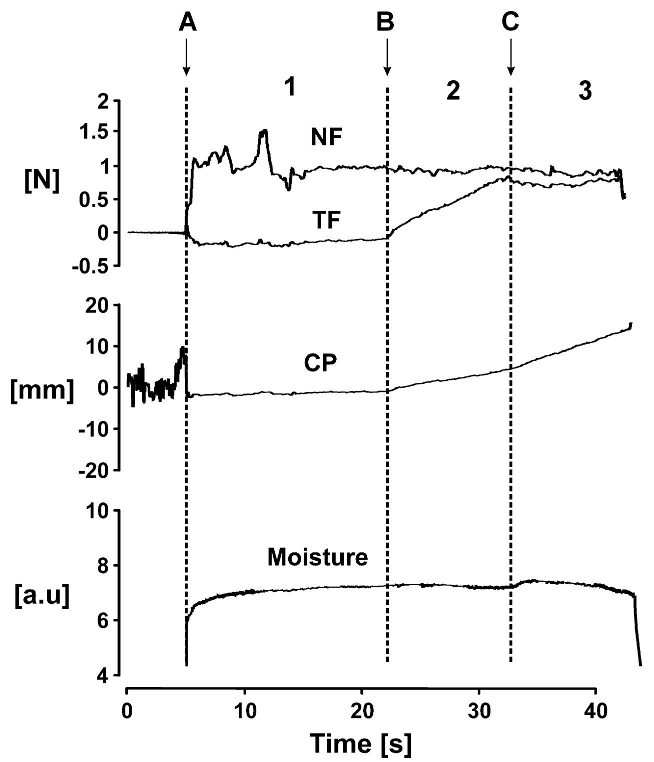

Fig. 2. Typical trial for one subject: evolution of the NF, TF, and CP of the thumb over time. (1) The subject stabilized NF. (2) The linear translation stage started to move and generated the vertical, monotonically increasing TF. The NF stayed constant during that period, whereas the CP varied slightly due to the compliance of the skin. (3) The TF reached a maximum, and the CP variation increased; the F/T sensors started slipping across the fingertip.

an increase in the TF exerted on each finger while subjects were instructed to keep their NF constant at the instructed level. When the TF became sufficiently large, the object slipped; the static CF was estimated at slippage by:

$$\mathrm{CF} = \frac{\mathrm{TF}}{\mathrm{NF}}. \quad (1)$$

Detection of slippage was performed combining two criteria: a maximum in TF associated with a steeper slope in the CP profile (Fig. 2; vertical line C).

Each subject performed five consecutive trials for seven levels of NF: 0.2, 0.5, 1, 2, 5, 10, and 25 N.

2.3. Data processing

The signals from the force transducers were low-pass filtered with a fourth-order zero phase-lag Butterworth filter having a cut-off frequency of 10 Hz, which is consistent with the bandwidth of the signals in this task. For each trial, the static CF was estimated separately for each finger when the object slipped. Skin hydration was also measured simultaneously using the Moisture Evaluator. The quantitative results were reported for both fingers (see Table 1) but the figures illustrate the data from the thumb.

Table 1
Effect of moisture on parameters *a* and *b* in Eq. (2) for the thumb and index finger.

$\mathrm{CF} = a\mathrm{NF}^{-b}$	*a*_thumb	*b*_thumb	R^2	*a*_index	*b* index	R^2
Dry	0.73	0.24	0.7	0.75	0.24	0.89
Normal	0.93	0.25	0.72	0.79	0.22	0.55
Wet	0.97	0.23	0.77	0.85	0.22	0.79
Very wet	0.8	0.11	0.24	0.75	0.14	0.75

2.4. Statistical analysis

The relationship between the NF and CF was quantified using a non-linear regression. The functional form was modeled according to the proposal of Wolfram (Wolfram, 1983), which hypothesized a negative power function between the CF and NF. Consequently, our non-linear regression was based on the following equation:

$$\mathrm{CF} = a\,\mathrm{NF}^{-b}, \quad (2)$$

where *a* and *b* are real parameters of the fit (‘FIT’ function of Matlab). All statistical analyses were performed using two-way analyses of variance (ANOVAs) to study the effects of seven levels of NF (factor 1) and four levels of moisture (factor 2) on the CF (data).

3. Results

Fig. 2 presents the temporal variation of the normal and tangential forces, as well as the vertical component of the center of pressure (CP) and the moisture during one typical trial for the thumb. For this particular trial, the subjects were instructed to maintain a constant NF of 1 N. During phase 1 of the experiment, the subject touched the object (position A in Fig. 2) and stabilized the normal force to approximately 1 N. For phase 2, the linear motor started to move (position B in Fig. 2) and the TF increased monotonically. During this period, the CP moved slowly due to the skin’s compliance. At the end of phase 2 (position C in Fig. 2), slipping occurred when the NF could no longer counteract the TF. The ratio of TF/NF at this time corresponds to the static coefficient of friction. During phase 3, the TF remained roughly constant and the slope of CP increased significantly.

3.1. Effect of normal force on the static coefficient of friction

The relationship between the normal force and static coefficient of friction for the four ranges of moisture previously defined is illustrated for the thumb in Fig. 3. This figure shows the pooled data for all subjects. For all ranges of skin hydration, the CF was low and constant for high levels of NF (>3.5 N). However, for three ranges of hydration (dry, normal, and wet; Fig. 3a–c, respectively), there was a large increase in the CF for low levels of NF (≤3.5 N). When the skin was very wet (Fig. 3d), this increase was much smaller. When the same analyses were performed on each subject individually, the same trends were observed as those in the pooled data for each range of moisture covered by each individual subject.

Negative power functions were used to quantify the relationship between the CF and NF (using a non-linear fit). Table 1 gives the values of the parameters *a* and *b* (see Eq. (2)) for the thumb and index finger across the four ranges of moisture. Parameter *a* was mostly influenced by the mean level of the CF (larger for normal and wet conditions). Indeed, it corresponds to the CF value when the NF = 1 N. Parameter *b* was closely related to the shape of the curve, as determined by the influence of NF on the CF. Parameter *b* was significantly smaller for the very wet range of moisture, indicating that the influence of NF on the CF was less important in this condition.

The statistical analyses using a two-way ANOVA showed that the interaction between NF, moisture level and CF was significant ($P < 0.01$). Nevertheless, the non influence of NF on CF for the very wet moisture level was confirmed: there was no significant differences across the seven levels of NF ($P > 0.01$, ANOVA), except when comparing the 0.5 and 10 N groups ($P < 0.01$, pairwise comparison using Dunn’s method).

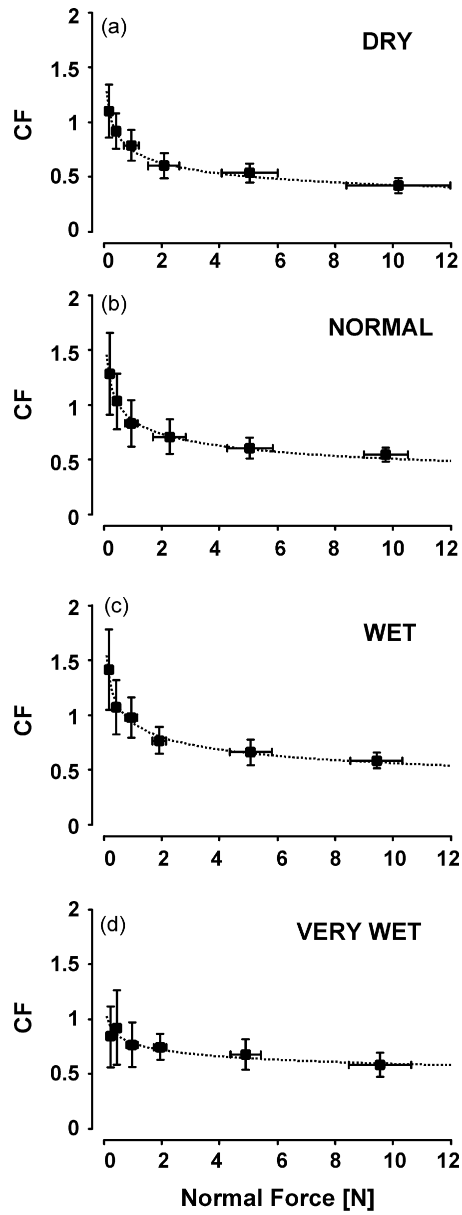

Fig. 3. Relationship between the CF and NF for the four moisture ranges. Each data point corresponds to the mean CF and NF for a specific range of NF pooled for all subjects (data for the thumb). The associated standard deviations (vertical for the CF and horizontal for the NF) are plotted around the corresponding means. The dashed curves show the negative power function regression line fit to all raw data (Eq. (2)). The largest value of NF tested (NF = 25 N) is not shown due to scaling constraints.

3.2. Effect of moisture on the static coefficient of friction

Fig. 4 presents the relationship between the moisture level and static coefficient of friction for seven different ranges of NF between 0.2 and 20 N. There was a significant influence of moisture on the CF for levels of NF $\leq$3.5 N (Fig. 4a–d). Indeed, the CFs for the normal and wet conditions (filled symbols) were significantly larger ($P < 0.01$) than those for the dry and very wet conditions (open symbols). The relationship between moisture and the CF could be approximated by a bell-shaped curve, with a peak CF for an intermediate value of moisture (approximately 7.5 a.u. on average). Moreover, when the NF increased from 0.2 to 3.5 N, the average CF level tended to decrease for the same values of moisture (consistent with the results of Fig. 3). For a NF > 3.5 N, the bell-shaped relationship was attenuated (Fig. 4e–g). The comparison between the normal and wet conditions and the dry and very wet conditions showed no statistically significant difference ($P > 0.01$) for NF > 3.5 N.

3.3. Estimation of the static coefficient of friction based on the moisture measurement and normal force

The values of parameters a and b in Eq. (2) (see Table 1) can be used to provide for each finger an estimate of the CF for each moisture range. Here, we propose a systematic method for estimating the static coefficient of friction for each condition. This method requires only the moisture measurement and normal force. The moisture is first used to determine the best parameter values for a and b that will be used to estimate the CF on the basis of the NF. Determining these parameters is based on a linear interpolation across values formed from the four moisture ranges defined above. This is illustrated in Fig. 5a, which clearly shows the association of a pair (a, b) for each measured value of moisture. The final step simply consists of inserting the (a, b) pair into Eq. (2) prior to estimating the CF. The final result is illustrated for the thumb in Fig. 5b and shows the 3D representation of the CF as a function of moisture and normal force.

4. Discussion

The aim of this paper was to study the combined effects of moisture and normal force on the static coefficient of friction of the skin for a fingertip during object manipulation. We developed a new method that allowed us to evaluate the CF during a precision grip by simultaneously measuring the normal force and skin hydration for a subject's fingertip. Our results indicate that (1) except at very high levels of skin moisture, the CF decreases with the NF according to a negative power function and (2) a bell-shaped curve characterizes the relationship between the CF and moisture, with an intermediate level of moisture maximizing the CF. This study clearly demonstrates the significant influence of both parameters on the CF, particularly at low NF levels (< 3.5 N).

The mechanical properties of the fingertip skin are of prime importance to understand human grasping and psychophysics of touch. More specifically, the coefficient of friction between fingers and objects is a critical parameter when manipulating objects. Until now, evaluation of the CF could only be done before or after a task, performing slippages and measuring the ratio of TF/NF when slipping was initiated. Our set of data combined with our method permit the continuous estimation of the CF during the entirety of any manipulation task.

Typical ranges of grip force used in dexterous manipulation are between 1 and 4 N (Johansson and Westling, 1984; Edin et al., 1992), and our results demonstrate the extent of CF variation for low levels of NF (<3.5 N): the CF is strongly influenced by both the NF and moisture. Moreover, we observed important moisture variations during a manipulation task (personal observations). These observations lead to the conclusion that the CF could vary significantly and that it is crucial to assess the CF during object manipulation. Our results allow us to take these variations into account and estimate the CF continuously. New perspectives of research that will consider these variations and study the way humans adapt manipulation strategies are now possible using the methods proposed in the current paper.

The influence of the NF on the static coefficient of friction has been described by several authors. Some of these studies did not find a significant effect of NF on the CF (Buchholz et al., 1988; Savescu et al., 2008), which can be explained by the high levels of NF (> 3.5 N) used in the respective experiments. In contrast, Comaish and Bottoms (1971) demonstrated a deviation from Amonton's law

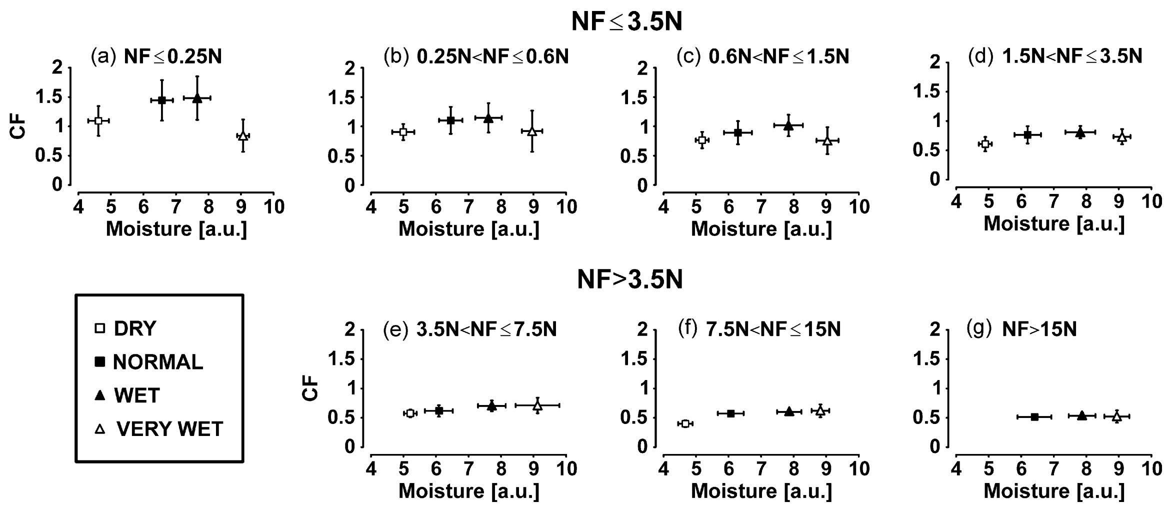

Fig. 4. Relationship between the CF and moisture of the thumb for seven different ranges of NF from below 0.25 N to above 15 N. Each data point corresponds to the mean CF and moisture content for the specific moisture ranges and for all subjects pooled together. The associated standard deviations (vertical for the CF and horizontal for moisture) are also plotted. The inset shows the four symbols used for the four different moisture ranges: open square (dry), filled square (normal), filled triangle (wet), and open triangle (very wet).

and high CF levels when the NF was extremely low. This study also formalized a more complex non-linear relationship between the NF, TF, and CF. The non-linearity of the CF with respect to the NF, especially for low levels of NF (< 3.5 N), has been demonstrated by other authors as well. Wolfram (1983) argued that the static coefficient of friction of the skin decreased as a negative power function of the NF (Eq. (2) with $b = 1/3$). Similar results have been reported

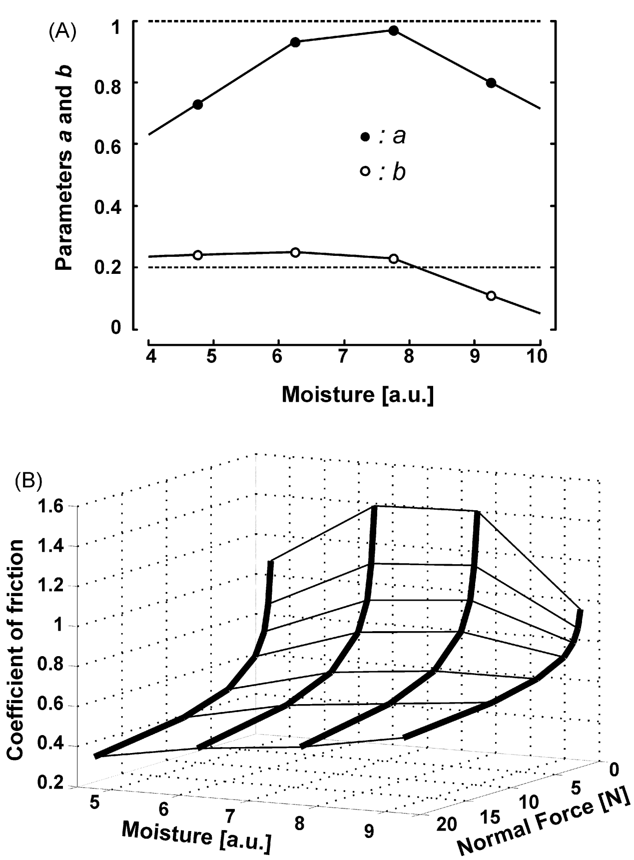

Fig. 5. (a) Estimation of a and b parameters (Eq. (2)) as a function of moisture (data for the thumb). The estimate is based on a linear interpolation across values found for a and b for the different moisture ranges (Table 1). (b) Estimation of the CF of the thumb as a function of moisture and NF (3D plot).

in publications that studied the static coefficient of friction of the skin on the dorsal side of the forearm using a glass probe or on the top of the middle finger using a steel probe (Koudine et al., 2000; Sivamani et al., 2003; Adams et al., 2007).

In the present work, we focused on the fingertip CF using a precision grip, because this approach determines the minimal grip force needed to avoid slipping of the object. Our results for the relationship between the CF and NF, expressed in Eq. (2), are consistent with the previous works cited above. Moreover, it has been shown that moisture influences the CF (Adams et al., 2007) as well as the relationship between the NF and CF (Derler et al., 2007). This is consistent with our results which showed an increase in CF with moisture. Moreover, our results covered a larger range of moisture level (i.e. the very wet condition in which CF dropped) and provided estimates of CF for a continuous moisture scale. In the present study, we demonstrated the importance of the combined measure of moisture and NF for estimating the CF.

Variations of the a parameter in Table 1 suggest that the moisture content also influences the CF. Indeed, Fig. 4 shows that CF values were strongly modulated by skin hydration. The effects of moisture on the CF varied between 46% and 4% for a NF range between 0.2 and 20 N, respectively. Up to now, various studies have considered the importance of the skin hydration level on performance during object manipulation. Smith et al. (1997) investigated the influence of scopolamine on the prehensile force during object manipulation and showed an increase of this force due to a reduction of palmar sweating. In the same way, Zackrisson et al. (2008) reported that a significant decrease of the CF and consequent significant increase of the grip force were observed when patients with very high sweating rate (hyperhidrosis) manipulated objects. These studies provide evidence for the importance of measuring skin moisture for fingertips during object manipulation, because this parameter significantly influences subject performance. Interestingly, these two studies that explore extreme ranges of moisture are fully compatible with our results (bell-shape, Fig. 4). From a mechanical point of view, the effects of moisture on the CF have been studied by comparing dry and moist conditions (Comaish and Bottoms, 1971; Buchholz et al., 1988) or by observing CF variation during drying or hydration periods (Sivamani et al., 2003; Adams et al., 2007). These studies showed an increase of the CF with moisturization. Nevertheless, none of these studies could report skin hydration measurements during the experiments. Our Moisture Evaluator (André et al., 2008) permitted a continuous measurement of moisture content and, most importantly, allowed for better discrimination of extreme and intermediate moisture values during the experiment. Fig. 4 shows the effects of moisture level on the CF for different moisture ranges and points to an optimal level of moisture for maximizing the CF.

Interpretations of the combined effects of NF and moisture on the CF were first offered by Bowden and Tabor (1967), who argued that the visco-elastic nature of the skin causes the true area of contact to be no longer proportional to the NF level. Accordingly, Buchholz et al. (1988) hypothesized that hydration of the skin would enhance its viscous properties which would augment the adhesion effect. Recently, Adams et al. (2007) explained this by modeling the hydrated *stratum corneum* as a soft elastomer; their Young's modulus values are comparable, and the relatively large compliance of the asperities results in smooth contact on the molecular level. Both the reduction in the elastic modulus and the swelling that occurs in water would be expected to lead to extensive smoothing of wet skin's frictional contacts. Moreover, the increasing liquid-bridging between the ridges of the skin and the contacted surface increased friction (Dinç et al., 1991). Finally, the pronounced decrease in the CF at very high levels of moisture could be explained by the presence of a thin layer of water between the skin and the object (Adams et al., 2007; Tomlinson et al., 2007).

The goal of this paper was to examine the combined effects of normal force and moisture content on the static coefficient of friction between the skin of a fingertip and a manipulated object and to propose a new method for its estimation. A global relationship (illustrated in Fig. 5b) showed the "cross-talk" of these two parameters on the CF. Our results yielded a new method for estimating the CF with NF and moisture measurements. Indeed, as presented in our results section, the moisture level measurements provided numerical values for our a and b parameters that define the negative power function for determining the CF. Thus, a continuous estimate of the CF can be obtained during the performance of dexterous manipulation. This measurement is of prime importance, particularly during situations with variable friction. For example, variable friction occurs when there is strong moisture variation or when the level of NF exerted on the object is very low (i.e. dexterous manipulation of very small objects or manipulation in a weightless environment). In this study, we quantified the influence of moisture on the CF, assessed the strong interaction of NF and moisture on the CF, and provided a method for estimating the CF that takes into account these two variables.

The method proposed here makes a major contribution to the field of object manipulation. It provides an estimation of the CF based on the moisture and NF measurement. This estimation does not require any slippage and can take into account the moisture and NF variation during manipulation. Indeed, moisture can vary with stress and the psycho-galvanic reflex but also according to the occlusion occurring at fingers-object interface. As we already know, the NF is permanently adapted to the inertia of the manipulated object. In future investigations it will be now possible to monitor the CF continuously during object manipulation taking into account the effects of moisture and NF on CF.

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