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Fingertip Moisture Is Optimally Modulated During Object Manipulation

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André T, Lefèvre P, Thonnard J-L. Fingertip moisture is optimally modulated during object manipulation. *J Neurophysiol* 103: 402–408, 2010. First published November 11, 2009; doi:10.1152/jn.00901.2009. Coordination between the normal force exerted by fingers on a held object and the tangential constraints at the fingertips helps to successfully manipulate objects. It is well established that the minimal grip force required to prevent an object from slipping strongly depends on the frictional properties at the finger–object interface. Moreover, interindividual variation in the modulation of grip force suggests that the moisture level of the skin could influence grip force strategy. In the present study we asked subjects to perform a horizontal point-to-point task holding an object with a precision grip. The object was equipped with a moisture sensor. We found large inter- and intraindividual moisture level variations. There was a strong correlation between grip force exerted and moisture level at the fingertips. Indeed, the grip force was minimal when the fingertip moisture was optimal with respect to friction. Furthermore, fingertip moisture tended toward this optimal level at which grip force is minimal. In conclusion, we showed a modulation of the grip force with moisture level and hypothesized novel mechanisms of moisture regulation that tend to stabilize the moisture level toward the value that minimizes grip force.

INTRODUCTION

When handling an object or transporting it through space we apply an adequately large force normal to the grip surface (grip force) in relation to destabilizing forces tangential to the grip surface (load force). Accidental slips rarely occur because the grip force exceeds the minimal force (dependent on load force and skin–object friction) required to prevent slip (Johansson and Westling 1984b). Skin–object friction is the force resisting the relative tangential motion between skin and object. This friction depends on the properties of the surface of the held object and the glabrous skin of the fingertips. Previously, a study by Johansson and Westling (1984b) revealed that the more slippery the object, the higher the grip force at any given load force. However, some pronounced interindividual variations of the friction between the skin and the surface materials were observed. Interestingly, these authors suggested that differences in sweating rates may partially account for this interindividual variability.

Although the importance of eccrine sweat secretion for controlling body temperature has been extensively investigated, the effect of sweating on the friction of glabrous skin in the palm and fingers of the hand has received comparatively little attention. Smith et al. (1997) reported that reducing spontaneous sweat gland activity of the hand by transdermal absorption of scopolamine, significantly decreased the friction of the fingers against a smooth plastic surface. In contrast, Zackrisson et al. (2008) reported that patients with primary palmar hyperhidrosis (abnormally high sweat) showed perturbed object manipulation caused by a decrease in friction. It has also been demonstrated in normal subjects that after washing and drying the hands, skin friction was greatly reduced compared with when moisture had time to accumulate (Johansson and Westling 1984a).

More recently, our group (André et al. 2009) reported that the relationship between the coefficient of friction and the moisture at the fingertip could be characterized by a bell-shaped curve, with an intermediate level of moisture maximizing the coefficient of friction. Thus the frictional properties of dry, damp, and wet skin were dissimilar. Damp skin was found to produce a higher frictional quality than that of either wet or dry skin. These observations led us to study the effect of fingertip moisture on grip force modulation during object manipulation. In a recent study we developed an instrument capable of measuring the moisture level of the skin (André et al. 2008). This device, called the Moisture Evaluator, enables the measurement of the water content of the skin surface during dexterous manipulation. In the present study we used the Moisture Evaluator to measure moisture variations at the fingertips during a manipulation task. We further examined the inter- and intrasubject moisture variations during the repetition of this task and the effect on grip force. We found that moisture level at the fingertip varies within and across subjects and that grip force is continuously modulated in accordance with moisture level. In this study we hypothesized novel mechanisms of moisture regulation that tend to stabilize the moisture around the value that minimizes grip force during object manipulation.

METHODS

In all, eight healthy volunteers (28 ± 9.6 yr) participated in this study. All subjects were right-handed according to the Edinburgh handedness inventory (Oldfield 1971). Subjects' vision was normal, or corrected to normal, and none had a neurological history. All experimental procedures were approved by the Ethics Committee of the Université catholique de Louvain and all subjects gave written informed consent. The temperature of the room was held relatively constant (23.8 ± 1.2°C) and air humidity was between 40 and 55%.

Apparatus

A manipulandum was held between the thumb and the index finger using a precision grip (Fig. 1). The manipulandum was equipped with two force-torque sensors, one under each finger (Mini40 F/T transducer; ATI Industrial Automation, Apex, NC). These sensors measured the three force components along the corresponding axes passing through the center of the corresponding grasp surface (Fx, Fy, Fz). Sensing ranges for Fx, Fy, and Fz were ±40, ±40, and ±120 N, with 0.01, 0.01, and 0.02 N nominal resolution, respectively. The

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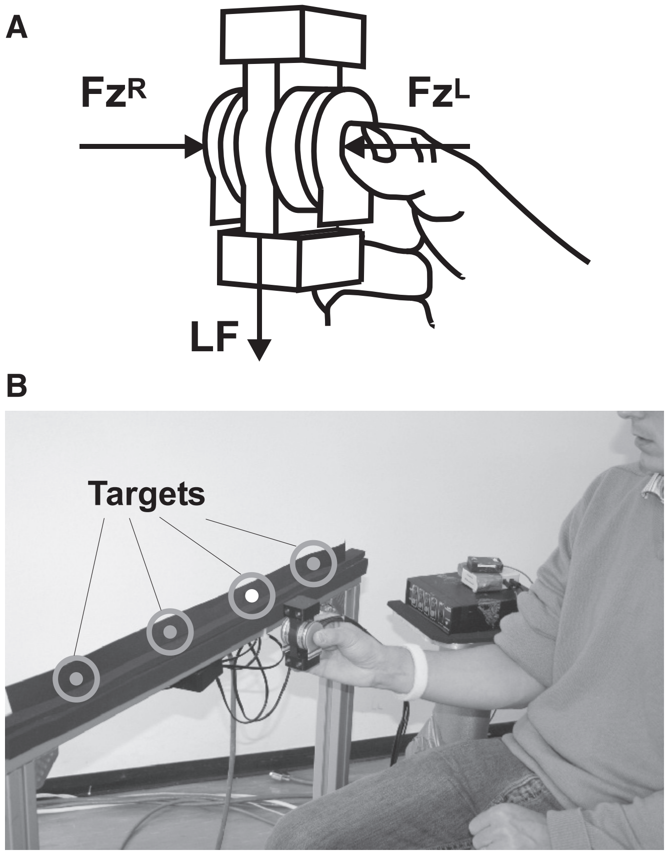

FIG. 1. *A*: the manipulandum is held between the thumb and index finger. The 2 normal grip forces (FzR and FzL) exerted by the fingers and the tangential load force (LF) are recorded. *B*: subjects were seated and told to move the manipulandum as fast as possible toward the illuminated target to align and stabilize the manipulandum in front of the target. Targets were randomly illuminated at the frequency of 1 Hz. One alignment corresponded to one trial and subjects performed 20 blocks of 25 trials each.

mass of the manipulandum was 0.26 kg and the width between the grip surfaces was 45 mm.

On both digits, skin hydration at the fingertip was measured with the Moisture Evaluator (André et al. 2008), consisting of an adapted probe fixed on a Bakelite support and an electronic circuit to evaluate skin conductance. The measurement of conductance is based on a resistor–capacitor circuit and is determined using a frequency measurement. A higher frequency signal represents increased water content at the skin surface. The frequency of the signal is recorded and reported on a logarithmic scale. The numeric scale of the Moisture Evaluator ranges from 4 to 10 in arbitrary units (au), representing very dry to very wet skin, respectively. André et al. (2008) demonstrated that the Moisture Evaluator actually measures the changes in moisture levels at the skin–object interface.

Experimental procedure

The task is illustrated in Fig. 1*B*. Four target light-emitting diodes (LEDs) were placed along a structure that was horizontally aligned with respect to the floor. The target LEDs were positioned every 15 cm. The program generated a random sequence of targets at a frequency of 1 Hz. The participant was seated in front of the target axis, held the manipulandum in a precision grip, and was asked to align and stabilize the manipulandum with the lit target until the next target was illuminated. Head, eye, and arm movements were not restricted. Each participant repeated 20 blocks consisting of 25 consecutive point-to-point movements each. Thus one block refers to 25 successive trials. Between each block the participant released the manipulandum for a 30-s resting period, during which fingertip moisture returned to baseline.

Data processing and variables studied

The signals from the force sensors were digitized at 800 Hz with a 16-bit NI9205 A/D converter plugged into a NI cDAQ-9172 chassis. After A/D conversion, the force signals were low-passed filtered with a fourth-order, zero phase-lag Butterworth filter with a cutoff frequency set to 15 Hz. The fingertip skin moisture level was measured by the Moisture Evaluator at target onset for each trial.

The normal grip force (GF) was defined as the average of the normal forces applied by the thumb and the index finger on each sensor and is represented by the following equation: $GF = (|Fz^R| + |Fz^L|)/2$, where Fz^R is the normal force component on the right sensor and Fz^L is the normal force component on the left sensor (Fig. 1*A*). The tangential force between each finger and the manipulandum was computed as: $Ft = \sqrt{Fx^2 + Fy^2}$. The load force (LF) was defined as the sum of the right and the left tangential forces: $LF = Ft^R + Ft^L$. It is worth mentioning that the difference between Ft^R and Ft^L was very small and always remained <5% of their mean for each component (x and y). Finally, for each trial, an average static GF (GFs) was computed in a 100-ms time window following the target onset (Fig. 2, gray bar). In other words, the average GFs represents the mean GF during which the manipulandum was held steady in front of the illuminated target. In each block, 25 values of GFs were associated with a corresponding value of moisture (mean of the right and left moisture values). This provided 500 pairs of GFs–moisture data points for each subject.

Statistical analyses were performed using least-squares linear regressions. The regression permitted us to evaluate the significance of a trend when testing the relationship between two variables (given by the *P* value). Moreover, the sign of the slope gave the nature of the effect.

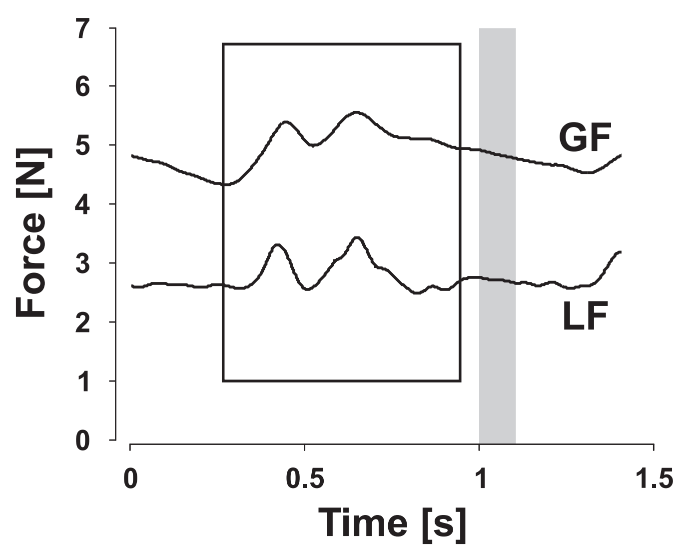

FIG. 2. Representative temporal alterations of the grip force (GF) and the load force (LF) during a trial. During the dynamic phase (manipulandum moving toward target, rectangular box), a double peak of LF, resulting from acceleration and deceleration of the manipulandum moving toward the target, is observed. The associated GF modulation is shown. During the stable phase (manipulandum held immobile in front of target, gray bar), the LF is constant and corresponds to the weight of the object (0.26 kg). Static GF (GFs) is defined as the mean GF during this stable phase.

RESULTS

The temporal pattern of GF and LF for a typical trial is displayed in Fig. 2. A dynamic phase (rectangular box) during which the manipulandum was moved toward the illuminated target preceded a static phase (gray bar) during which the manipulandum was held stationary in front of the illuminated target. During the dynamic phase, the manipulandum was accelerated and decelerated to reach the illuminated target. Typically this movement triggered a double peak in the LF trace, with corresponding peaks in the GF trace. During the static phase, LF was constant and equal to the weight of the manipulandum (2.6 N). In this study we concentrated on the skin moisture variation during the static phase and its influence on GFs.

Fingertip moisture, measured in arbitrary units, varied significantly across participants. We ranked the subjects according to their mean moisture level across 500 trials and found that participants with either very dry or very wet skin exerted higher GFs than participants with an intermediate moisture level (Table 1).

A significant effect ($P < 0.01$) of the block number on the GFs was observed for each individual subject (see Table 2), except for S4. The slope of the linear regression was positive for four subjects and negative for three subjects, indicating that, depending on the subject, GFs could increase or decrease across the blocks. Accordingly, when the data were pooled across all subjects, there was no significant effect of block number on GFs (repeated-measures ANOVA, $P = 0.35$; $\chi^2 = 20.82$; $n = 19$). These results indicate that there was no clear effect of repetition on GFs across all subjects.

After having studied the effect of the block number on GFs, the influence of the mean moisture inside a block on GFs was studied. The relationship between the mean GFs in each block and the corresponding mean moisture is shown in Fig. 3, pooled for the eight subjects. For a low level of moisture, the GFs decreased when the moisture increased until an intermediate value of moisture for which the GFs was minimal. For a high level of moisture, the effect of moisture was inverted and GFs increased again with moisture.

Fingertip moisture level during each trial was averaged across the 20 blocks for each subject (Fig. 4). When the mean value of the moisture was low during the first trial (S1, S2, S3, and S5), the moisture increased significantly ($P < 0.001$) across the 25 trials. When the moisture level was intermediate during the first trial (S4, S6, and S7) it did not change across trials ($P > 0.05$). Finally, when the moisture level was high during the first trial (S8), it significantly decreased ($P < 0.001$) across trials.

We were interested in the pattern of GFs across trials for each subject. Figure 5 illustrates, for each subject, GFs across the 25 trials averaged for the 20 blocks. GFs decreased significantly ($P < 0.001$) across the trials for all subjects, except for S4 presenting low and constant GFs. Interestingly, at first glance these results were not as we expected. We were interested in a correlation between the moisture level and GFs. In a comparison of Figs. 4 and 5 a decrease in GFs across trials for S6 and S7 is associated with a constant level of moisture across trials. However, the variability of moisture level across all blocks was much higher during the first trials for these subjects, indicating that within each block the moisture could increase, remain stable, or decrease across the 25 trials. Thus we performed additional analyses to compare the pattern of moisture with the pattern of GFs across the trials within each block. To that purpose we sorted the 20 blocks of each subject according to the moisture pattern across trials within each block (Table 3). A block was classified in group 2 if the moisture level remained constant (the difference between the first three and last three trials was less than ±0.15 au), in group 1 if the moisture level increased (the difference between the first three and last three trials was greater than +0.15 au), and in group 3 if the moisture level decreased (the difference between the first three and last three trials was less than −0.15 au). For group 1, an increase in moisture was associated with a systematic decrease in GFs (all $P < 0.001$). For group 3, there was a decrease in moisture that was also associated with a decrease in GFs (all $P < 0.001$). In contrast, for group 2, neither moisture nor GFs varied (all $P > 0.05$, except for S3).

Figure 6 presents the results of S6 to illustrate the three tendencies described earlier. When moisture increased across trials (Fig. 6, *left column*, low level of initial moisture), there was an associated decrease of GFs ($P < 0.001$).

TABLE 1. *Mean value (±SD) of moisture and static grip force (GFs) for each individual subject across 500 trials*

Subject	Moisture, au	GFs, N
S1	5.6 ± 0.62	10.9 ± 2.05
S2	6.4 ± 0.89	8.6 ± 2.15
S3	7.3 ± 0.94	6.6 ± 1.34
S4	7.7 ± 0.86	5.2 ± 0.75
S5	7.8 ± 0.98	5.1 ± 0.93
S6	7.8 ± 1.06	5.7 ± 1.14
S7	8.1 ± 1.01	8.7 ± 1.01
S8	8.8 ± 0.93	8.5 ± 1.89

TABLE 2. *Effect of the block number (repetition of the task) on GFs for each individual subject*

Subject	*P* Level	Slope
S1	<0.01	0.120
S2	<0.01	−0.36
S3	<0.01	0.028
S4	0.49	NA
S5	<0.01	0.029
S6	<0.01	0.030
S7	<0.01	−0.130
S8	<0.01	−0.080

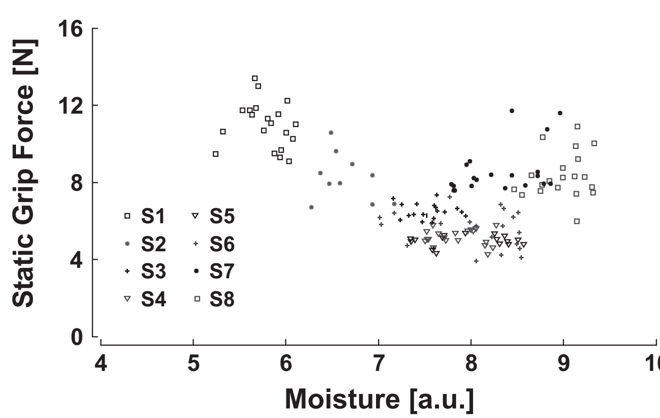

FIG. 3. The relationship between the mean GFs of each block and the mean moisture level within the same block for each of the 8 subjects. Data for each subject are represented with a different symbol.

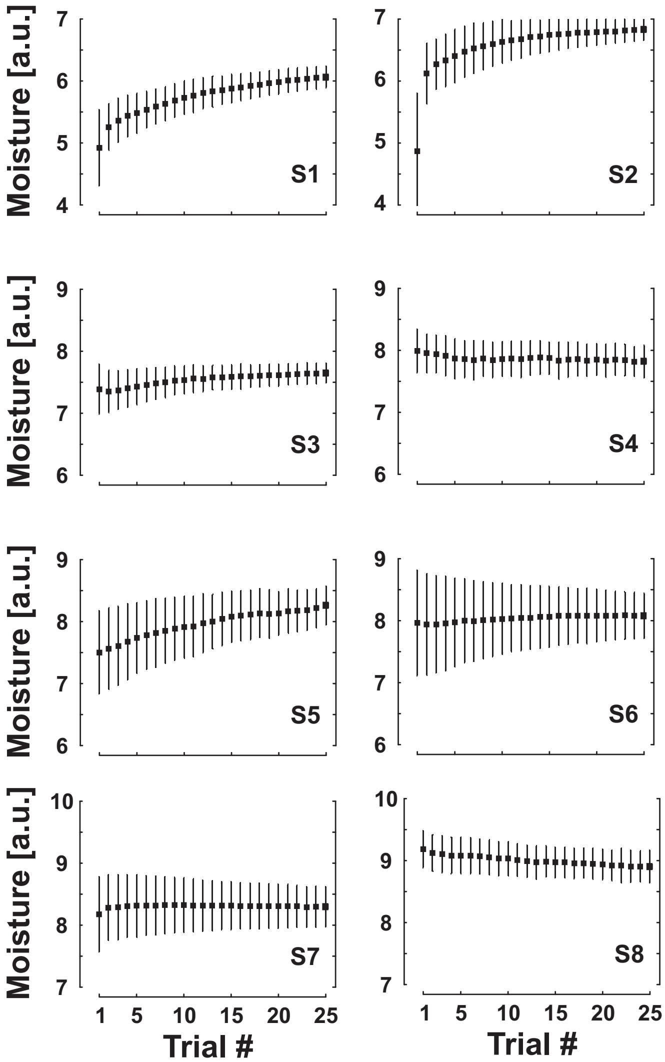

FIG. 4. Skin moisture level at the fingertip across the 25 trials, for each of the 8 subjects. Each data point corresponds to the mean moisture level for each trial, across all blocks. The associated SDs (vertical line) are plotted around the corresponding means. Three tendencies are demonstrated: increase of moisture level with trials (S1, S2, S3, and S5); constant moisture level across trials (S4, S6, and S7); and decrease of moisture level with trials (S8).

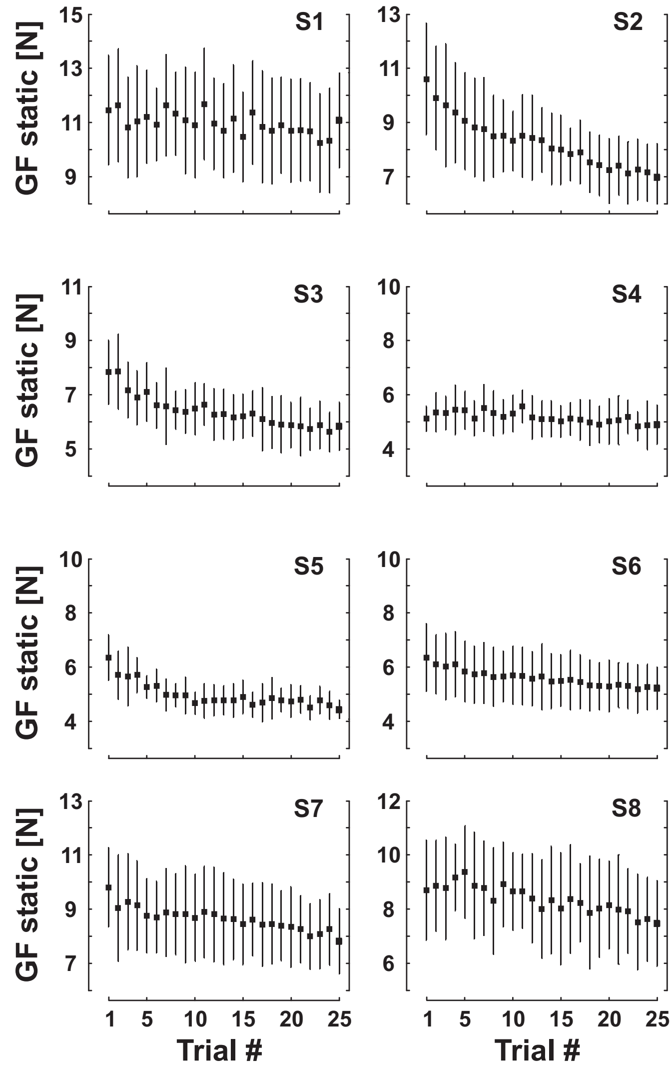

FIG. 5. GFs exerted across the 25 trials, for each of the 8 subjects. Each data point corresponds to the mean GFs for each trial across all blocks. The associated SDs (vertical line) are plotted around the corresponding means. Two trends are demonstrated: a decrease in GFs with trials (all subjects except for S4) and constant GFs across trials (S4).

When moisture decreased across trials (Fig. 6, *right column*, high level of initial moisture), there was also an associated decrease in GFs ($P < 0.001$). Interestingly, when moisture remained stable across the trials (Fig. 6, *middle column*), there was no modulation of GFs ($P = 0.15$). These results demonstrate that even within individual blocks, the changes in GFs were modulated by the pattern of fingertip moisture across trials.

The modulation of GFs with skin moisture appears clearly when all 500 pairs (25 trials in 20 blocks) for each subject are plotted (Fig. 7). It is interesting to observe that most of the trials are concentrated around the intermediate level of moisture (~8 au). Moreover, these results suggest that there is an optimal level of moisture at which GFs is minimized. The relationship between GFs and moisture level can be fitted well by a quadratic regression: $y = 1.15x^2 - 17.8x + 75.1$ ($P < 0.001$; $R^2 = 0.45$), for which a moisture value of 7.75 au minimizes GFs.

DISCUSSION

The present study focused on the effect of skin moisture at the fingertip on grip control during dexterous manipulation. By measuring the moisture level and the force exerted on an object

TABLE 3. *Percentage of blocks (across the 20 blocks) that belonged to each category, depending on the moisture variation, for each individual subject*

Subject	Moisture Increase Group 1	Moisture Constant Group 2	Moisture Decrease Group 3
S1	100%	0%	0%
S2	100%	0%	0%
S3	70%	20%	10%
S4	0%	100%	0%
S5	95%	5%	0%
S6	30%	20%	50%
S7	55%	5%	40%
S8	0%	0%	100%

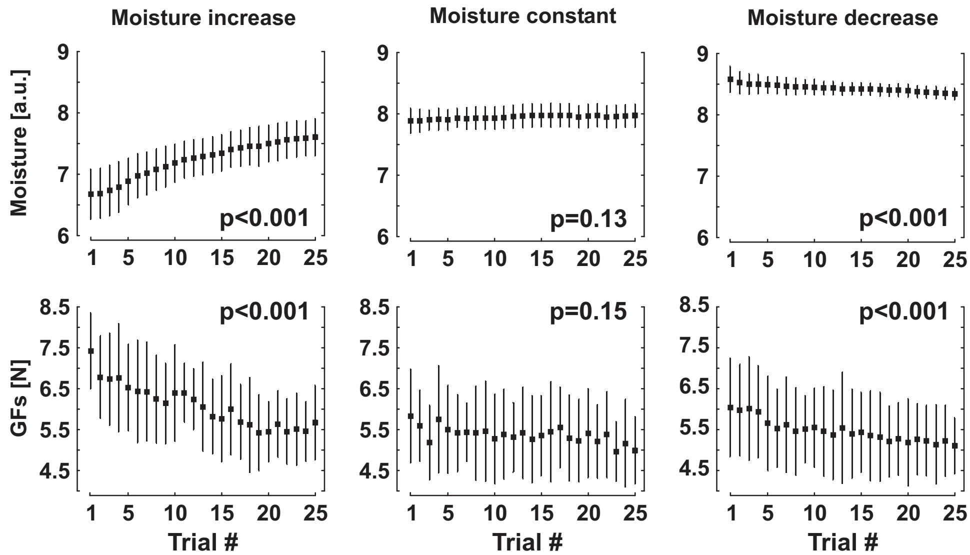

FIG. 6. Representative alterations in moisture level and GFs with trial number (for S6). Three groups, defined by moisture variation during blocks, are represented (moisture increase, moisture constant, and moisture decrease). Each data point within a graph corresponds to the mean moisture level for each trial, across all blocks. The associated SDs (vertical line) are plotted around the corresponding means. The *P* values of the linear regression fitting the data are given for each relationship.

held in a precision grip during a point-to-point task, we demonstrated that human subjects adjust grip force with the moisture level. Our results showed that *1*) skin moisture level at the fingertip varied significantly from one subject to another and also across trials for each subject and *2*) grip force was adjusted continuously to adapt to the moisture level during the task.

The influence of extreme skin moisture conditions on grip force has previously been studied. Very dry skin, resulting from the effect of aging (Cole 1991) or from scopolamine administration (Smith et al. 1997), has been shown to increase the level of grip force. Additionally, very wet skin in a patient with hyperhidrosis (Zackrisson et al. 2008) resulted in an increase in grip force. In these studies, it has been hypothesized that an increase of GF is due to a reduction in the friction coefficient. Our results agree with these prior studies (Table 1) and provide evidence from natural ranges of moisture observed in normal subjects. Subjects with very low or very high values of moisture exerted a higher grip force. The effect of moisture on fingertip skin friction was previously analyzed. Buchholz et al. (1988) reported that the presence of moisture resulted in an increase of the friction coefficient for handling of porous materials (adhesive tape, suede, and paper). Derler et al. (2007) showed that the variations in friction coefficients measured between human skin and a reference textile were mainly attributed to differences in skin hydration and variations in the lipid content at the skin surface. More recently, we further characterized the effect of moisture at the fingertip by measuring the alterations of this value during object manipulation (André et al. 2008) and by studying its effect on the skin's static friction coefficient (André et al. 2009). In the latter study, we reported a strong influence of moisture level on friction, which is especially noticeable for a low level of normal force, at which an optimal level of moisture maximizes friction. From a more mechanistic perspective, Adams et al. (2007) studied the coefficient of friction of the skin with a sphere sliding on the forearm. They compared skin behavior for different skin moisture levels and explained mechanically the role of moisture on the coefficient of friction. They distinguished three hydration states (dry, damp, and wet) and found a peak in coefficient of friction for damp skin. In the same way that Warman et al. (2009) analyzed the effects of fingerprints on fingertip friction, a model of the fingertip skin mechanical properties should be developed and should integrate the role of moisture.

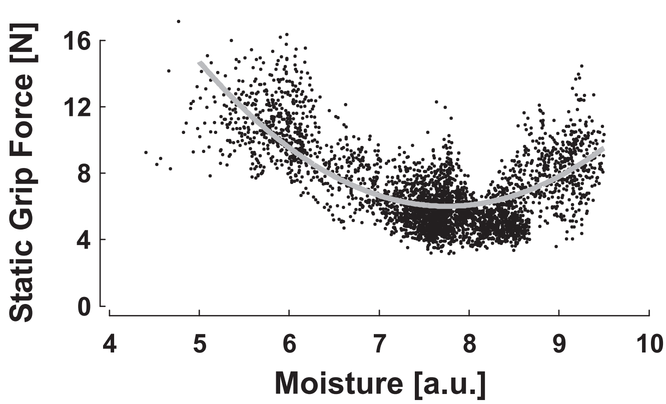

FIG. 7. Relationship between GFs and moisture level for the raw data. Each point corresponds to paired GFs–moisture level. The 500 paired GFs–moisture level are represented for each subject. The gray trace illustrates the quadratic regression fitting the raw data ($y = 1.15x^2 - 17.8x + 75.1$) with the minimum in GFs–moisture value pairing equal to 7.75 arbitrary units.

Previous studies have not taken into account variability in fingertip moisture level during object manipulation. In the present study, we continuously measured the skin moisture level together with the force exerted on an object and found that the grip force was actively and dynamically modulated with moisture level variations. Figure 6 illustrates both moisture and grip force level variations in one subject. As can be seen, when the fingertip moisture level starts at one extreme, it tended to increase or decrease to an intermediate value and this alteration in moisture was accompanied by a reduction of grip force. In addition, when the fingertip moisture started at an intermediate level, moisture did not tend to increase or decrease and grip force remained constant (Fig. 6, *middle column*). This tendency for the moisture level to reach an intermediate value with a concomitant decrease in grip force was confirmed for all the subjects (Table 3). Moreover, it was shown that the grip force decrease was not due to repetition of the task (no block effect in Table 2).

Adams and Hunter (1969) studied the effects of sweat secretion via stimulation of the peripheral plantar nerve on footpad skin friction of anesthetized cats. They showed that the lowest levels of sweat secretion produced the greatest increases in friction. These results may be explained by changes in the stratum corneum, which becomes more pliable with increasing moisture level and more deformed by tangential forces. In the same study it was also reported that higher steady-state rates of sweating progressively decreased skin friction. Finally, in agreement with earlier studies (Buettner 1965; Darrow 1936; Weiner and Hellman 1960), Adams and Hunther (1969) confirmed that, rather than playing a strictly thermoregulatory role, sweat gland activity in the tactile skin modifies cutaneous mechanical properties. Later, Adelman et al. (1975) showed that sweating on the paws and palms serves several functions, all of which are advantageous to the exercising animal—it increases friction, toughness of the skin, and tactile sensitivity. Moreover, they postulated that this sweating prepared the animal to flee from stressful situations. Physiological adaptation of the palmar sweating function can theoretically be translated to humans in the context of fine pinch grip in the manipulation of small objects.

In our experiment, the fingertip moisture level presented variability when performing a task and tended to stabilize by the end of each block (Fig. 4). Additionally, when the moisture level was stable, the final value ranged from 6.5 to 8.5 au, whereas when it was more variable, it tended toward this range of values. Interestingly, this range can be considered optimal with respect to friction. Indeed, we have shown (André et al. 2009) that fingertip friction was maximal for moisture values ranging from 6.5 to 8.5 au, with an estimated friction maximum at 7.8 au. Remarkably, the present data (Fig. 7) show that the moisture value at which GFs was minimal was 7.75 au and that most of the data points (62.5%) of Fig. 7 were concentrated around this value (6.5–8.5 au). The r^2 presented on Fig. 7 is equal to 0.45, which means that 55% of the variation in grip force is due to factors other than moisture, such as the variability in the execution of the task both within and across subjects. One can observe that the sweating rate always evolved toward the optimal level of moisture with respect to skin frictional properties at the fingertip. Different mechanisms of active or passive regulation can be suggested at a peripheral or central level. Indeed, the regulation could be purely passive with the increase in moisture arising from occlusion at the finger–object interface when the baseline skin hydration is low and the decrease in moisture resulting from reabsorption when skin hydration is high. Another possible mechanism would be a peripheral control of the sweating gland rate that would be controlled to optimize friction. Finally, the possible control of the fingertip sweat gland activity by the CNS cannot be ruled out, but remains speculative. Further investigations on the mechanisms of modulation of fingertip sweat are necessary to clarify this question.

It has been well described in the literature that the frictional conditions at fingertip–object interface are coded during the loading phase when performing a grip lift task (Johansson 1991; Johansson and Westling 1984a,b, 1987). Stress of the skin deforms the mechanoreceptors and the microslips occurring on the border of the contact surface (called incipient slips) allow humans to code friction and adjust the grip force accordingly. In our task, the dynamic phase, during which the manipulandum moved, caused skin deformation and most likely microslips. This could allow subject to "reestimate" fingertip–object friction. However, the range of GFs exerted by subjects during the task in the present study was >3.5 N, which is a level of normal force we previously found associated with the moderate influence of moisture on fingertip friction (André et al. 2009). Using a method we previously developed (see André et al. 2009), we could estimate the coefficient of friction for two extreme values of GFs found in our present data. At one extreme, when the moisture was low (5 au), the GFs found with the quadratic regression (Fig. 7) was high (14.85 N). The estimated coefficient of friction was 0.4 for these conditions. On the other hand, when the moisture level was optimal (7.75 au), the GFs was low (6.22 N) and the estimated coefficient of friction was 0.64. We can therefore postulate that the adaptation of GFs exerted by subjects in the present study in response to moisture variation was highly sensitive: a decrease in friction of about 37.5% (from 0.64 to 0.4) was associated with an increase of about 138% in GFs (from 6.22 to 14.85 N). It is possible that this high sensitivity is a "safe" strategy used by the subjects to overcome the dramatic effect of extreme values of moisture on grip stability. Indeed, it appears that the subjects' grip adjustment was overcompensated in response to the effects of friction variation. It is also possible that at both extremes (very high and very low moisture levels) the certainty in friction estimation is more ambiguous and a greater GFs is required again as a "safe" strategy. One of the most exciting implications of this study is that the CNS might discern moisture level changes during object manipulation and make the necessary adjustments in grip force. The mechanism by which this information is communicated has still to be defined and is of interest for future study. Finally, it is worth noting that we tested only one surface and cannot make conclusions about the interaction between the changes in friction due to surface or moisture.

In conclusion, we found that moisture level was modulated to optimize skin mechanical properties. The physiological mechanism regulating moisture at the fingertip still remains to be further investigated. In parallel, GFs decreased when moisture levels tended toward an optimal value. The present data show clear evidence for a continuous modulation of GFs with skin moisture variation. Our results suggest that the sweat rate is modulated to optimize skin moisture and that the moisture level variation is taken into account to adequately adjust GFs.

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