Changes in Normal Force During Passive Dynamic Touch: Contact Mechanics and Perception

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***Abstract*— Using a force-controlled robotic platform, we investigated the contact mechanics and psychophysical responses induced by negative and positive modulations in normal force during passive dynamic touch. In the natural state of the finger, the applied normal force modulation induces a correlated change in the tangential force. In a second condition, we applied talcum powder to the fingerpad, which induced a significant modification in the slope of the correlated tangential change. In both conditions, the same ten participants had to detect the interval that contained a decrease or an increase in the pre-stimulation normal force of 1 N. In the natural state, the 75% just noticeable difference for this task was found to be a ratio of 0.19 and 0.18 for decreases and increases, respectively. With talcum powder on the fingerpad, the normal force thresholds remained stable, following the Weber law of constant just noticeable differences, while the tangential force thresholds changed in the same way as the correlation slopes. This result suggests that participants predominantly relied on the normal force changes to perform the detection task. In addition, participants were asked to report whether the force decreased or increased. Their performance was generally poor at this second task even for above-threshold changes. However, their accuracy slightly improved with the talcum powder, which might be due to the reduced finger-surface friction.**

I. Introduction

Humans must accurately perceive contact forces when they explore the properties of the surrounding environment [1] and when they optimize their behavior during object manipulation [2]. Hence, a loss of tactile sensation has severe consequences, greatly reducing one's capacity to cope with daily physical interaction challenges [3], [4].

The relationship between the normal and tangential contact forces during manipulation and their impact on grasping behavior have been extensively investigated in the literature [5]. Despite several studies highlighting the rich contact mechanics occurring on the fingerpad during dynamic touch [6], [7], [8], little is known about how the normal and tangential components of the contact force evolve when tactile features are dynamically explored, nor do we understand how their evolution affects their perception by humans.

Current knowledge about the perception of changes in the normal and tangential components of contact force has been gathered mostly during static touch paradigms simulating steady contact with an object. The psychophysical threshold for detecting changes in the tangential force was estimated when only cutaneous information was provided and showed a Weber ratio (75% JND) of 0.16 [9]. These authors, however, did not measure the detection threshold for normal force. Instead, they evaluated the human ability to estimate the magnitude of light normal forces up to 0.7 N [10] and of larger normal forces between 1 N and 5 N [9]. Their results suggest that humans can perceive a difference of about 0.1 N as subjectively different during the application of small normal forces. Another study investigated the perception of small tangential or normal displacements of a probe, which induced contact forces on the skin. This study found humans to be more sensitive to tangential displacements of the probe [11]. However, the authors also found that an identical displacement generated five times more force in the normal direction and that the force threshold was actually

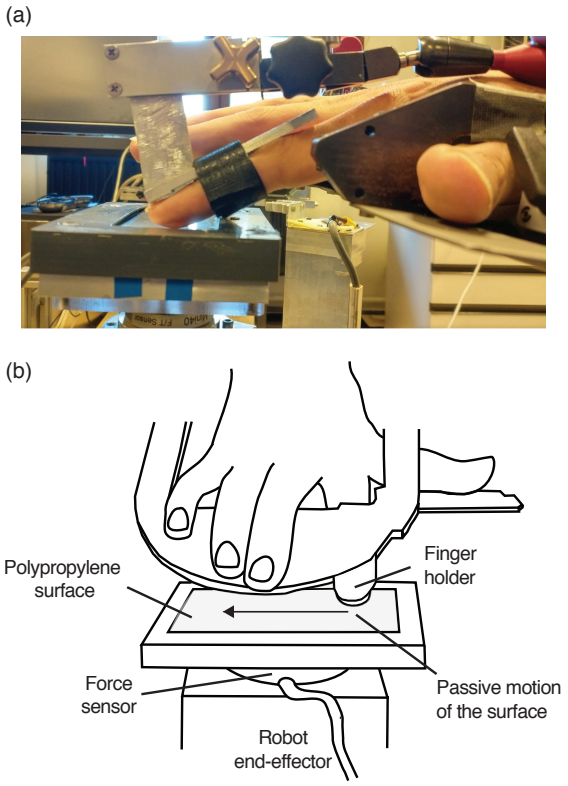

Fig. 1. (a) A robotic platform slides the surface across the index fingertip with controlled speed and normal force. (b) The hand and fingers are stabilized by holders while the surface rubs the fingertip.

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lower for normal force.

In dynamic touch, the contact forces applied to the finger have been shown to provide more prominent sensory cues than the geometry of the explored surface [12]. It was also suggested that shape-related tactile information is recovered more easily from shear strain than normal strain [13]. Although shear forces seem to be the primary cue during natural interaction, humans adjust their normal force in order to optimize their tactile sensitivity [14]. Moreover, a recent study on shape rendering via electrostatic friction modulation showed that virtual geometric features, such as bumps and holes, are difficult to render solely by frictional cues without additional context [15].

Our study centers on extensive psychophysical assessment of the human perception of decreasing and increasing modulation of the normal force in natural and low-friction conditions. To that end, we use a force-controlled robotic platform that is able to decrease or increase the normal force during a short interval in the middle of a sliding interaction; the normal force is otherwise kept constant. The low-friction condition is created by applying talcum powder to the fingerpad. Testing these two frictional conditions enables us to examine the relative importance of normal and tangential cues, which are linearly related within each condition [16]. We use recordings of the three-dimensional contact forces to analyze the evolution of the relationship between the normal and tangential components of the force.

In general, a better understanding of the relationship between changes in normal and tangential force applied on the fingerpad and their perception could impact the design of demanding haptic tasks such as recognition of virtual tactile features [15], [17], robot-mediated surgery [18], and delicate teleoperation [19]. In these applications, it is essential to understand how the normal force feedback impacts the perception of users in terms of both intensity and direction of variation to help them adapt their grasping and touch.

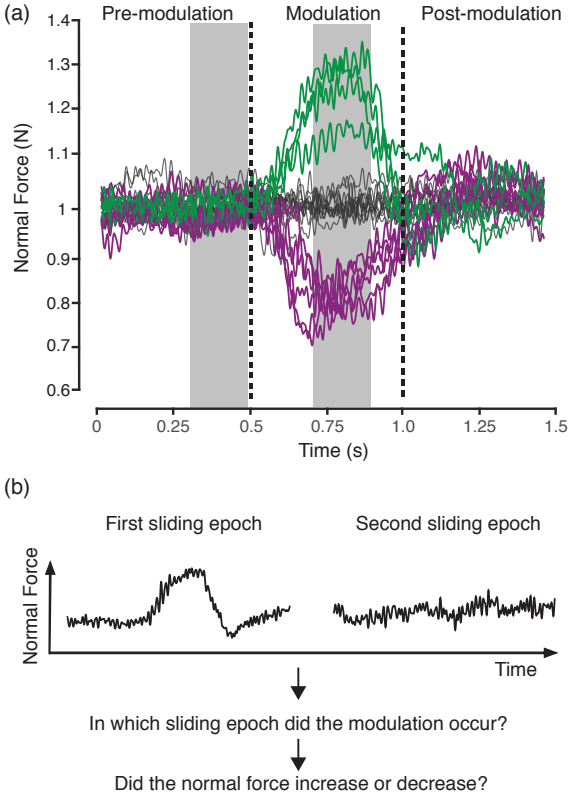

Fig. 2. (a) Time course of the normal force during several typical trials representative of the three conditions: the decreasing normal force with ΔF_n = -0.2 N (purple), the catch trials with a constant normal force of 1 N (gray), and the increasing normal force ΔF_n = +0.2 N (green). The gray lightly shaded areas represent the intervals that were used to compute the changes in the forces. (b) During each trial, the platform performed two consecutive sliding epochs. The force modulation was randomly chosen to be implemented in one of the two epochs. At the end of each trial, the subject reported the sliding epoch in which he or she perceived the force change, as well as the direction of the change in the normal force (decreasing or increasing).

II. Materials and Methods

Data were collected from 10 right-handed healthy volunteers aged between 23 and 56 (2 females) with a median of 31.5. This study was approved by the ethics committee on human research of Université catholique de Louvain. All participants gave written informed consent.

A. Experimental setup

We used a custom robotic platform designed to apply controlled stimuli to the fingertip during passive dynamic touch [20]. The robotic platform is based on an industrial robot (four-axis SCARA Denso HS-4535G) that is able to translate in three orthogonal directions (Fig. 1a). The end-effector's position is servo-controlled with a position resolution of 15 μm by a factory controller at a frequency of 1 kHz, which enables exact control of the instantaneous speed of the sliding. The subject's index finger was fixed in a support that maintains a constant angle of approximately 20 degrees between the finger and the stimulating plate (Fig. 1b). An ATI Mini40 load cell, with a single measurement resolution of 0.01 N in F_x and F_y and 0.02 N in F_z, is mounted on the robot to measure the normal force applied by the platform. The normal force is fed into and controlled by a proportional-integral (PI) controller. The tangential force depends on the interfacial material, the properties of the subject's fingertip, the presence of agents such as talcum powder, the sliding speed, and the current normal force.

B. General procedure

The study was conducted in a passive dynamic touch condition in which a smooth polypropylene surface was rubbed against the subject's static index finger. The robotic platform was programmed to deliver a precise stimulation of the fingertip, which consisted of a sliding distance of 5 cm at a speed of 2.0 cm/s with a constant normal force (NF) of 1 N (see also the supplementary video of a sample trial). This speed and normal force are typical of human haptic interactions and can be accurately generated by the robotic platform. Each trial included two consecutive sliding epochs against the fingertip. In one of the two sliding epochs, no modulation of the normal force was introduced, so the

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participant felt the surface with a constant normal force. In the other epoch, the normal force was modulated during an interval of 500 ms, which was programmed to start with identical timing in each trial. Three conditions were tested: an increase of the normal force, a decrease of the normal force, and a catch trial condition (Fig. 2a). The commanded amplitudes of the change in NF consisted in decreasing or increasing the constant NF by 0.1 N, 0.2 N, 0.3 N, and 0.4 N. The catch trial condition contained no variation in NF beyond the constant force level of 1 N. This ninth condition was implemented to test for possible perceptual biases during the experiment. Each of the nine distinct stimulation levels was repeated 10 times, and all trials from the three conditions were presented in a pseudo-randomized order for a total of 90 trials. Participants were prevented from watching the stimulation to avoid visual cues. There were no discernible auditory artifacts, so we did not use noise-cancelling headphones. The surface was cleaned with commercial glass cleaner before each experiment. During the experiment, we removed visible talc residues, but no cleaning was performed to avoid changing the state of the fingerpad.

During the experiment, participants had to perform a forced-choice task (Fig. 2b) to state which of the two sliding epochs contained the change in NF (detection task) and in which direction (decreasing or increasing) they felt the change. Both answers were verbally reported immediately after each trial in this order.

C. Talcum powder on the fingerpad

Participants were asked to perform the same experiment both without and with talcum powder applied to their fingerpad. When used, the talcum was applied immediately before the experiment and after each block of 30 trials in order to absorb skin moisture and reduce the finger-surface tangential force. Talcum powder has the advantage of strongly reducing the finger-surface friction without changing the explored material. Participants performed the experiment with talcum powder seven months after performing it without.

D. Computation of the force signal

The interfacial forces F_x, F_y, and F_z were recorded during the entire contact between the platform and the finger using the ATI Mini40 load cell. The force data were filtered by a second-order non-causal low-pass Butterworth filter at 40 Hz to remove the frequency components induced by the vibrations of the moving robot. The tangential force (TF) at each time step was computed from the x and y tangential force recordings using the following equation:

$$TF = \sqrt{F_x^2 + F_y^2} \tag{1}$$

To prevent any residual force oscillations from affecting the results, the changes in the normal and tangential forces were computed as the ratio between the mean force during a 200 ms interval within the 500 ms modulation (200 ms were excluded at the start and 100 ms at the end to eliminate the transitional phases) and the mean of the force during the 200 ms pre-modulation interval (Fig. 2a). The short duration of the pre-modulation interval also limited the potential impact of occlusion on the force analysis. To evaluate the stability of the normal force (NF) control, we computed the standard deviation of NF during the one-second interval prior to the induced change in NF. The standard deviation was always lower than 0.06 N for all the stimulation levels, showing that the robotic platform accurately controlled the normal force. Thus, even the smallest predefined level of change in NF is twice as large as the average noise in the forces, which enables the possibility of its perception providing sufficient tactile acuity.

E. Statistical and psychometric analyses

Parametric or non-parametric statistical analysis of a given data sample is motivated by the D'Agostino and Pearson omnibus normality test, which we performed on all analysed samples using GraphPad Prism software. We defined the 75% just noticeable difference (JND) as the ratio between the change in NF and its pre-stimulus value that was correctly perceived in 75% of the trials. The ratio at the 75% JND, also known as the Weber ratio, was computed for each individual participant by fitting a logistic psychometric function to the proportion of correct detection responses. The average psychometric curves were then computed based on the median values of the thresholds and slopes across all individual psychometric functions. The psychometric fittings were performed using dedicated functions of the Palamedes toolbox [21].

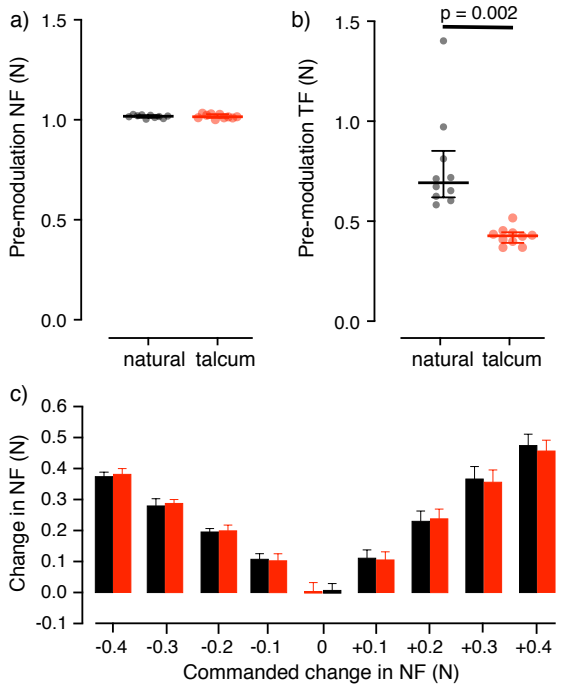

Fig. 3. (a) Mean normal force during the 200 ms before the start of the modulation (mean ± s.d.) (b) Mean tangential force during the 200 ms before the start of the modulation (mean ± s.d.) (c) The actual computed change in NF for each of the predefined levels of modulation (mean ± s.d.) for the natural friction condition (black) and when talcum powder was applied (red).

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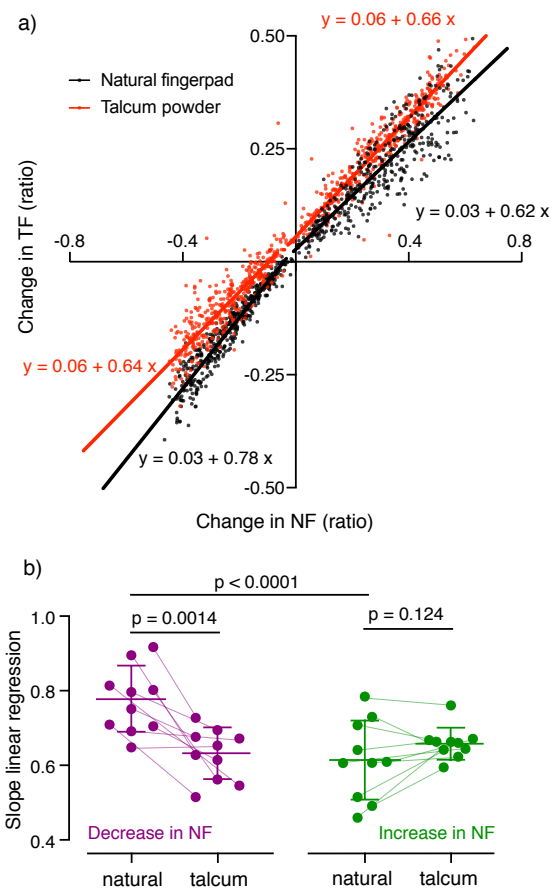

Fig. 4. (a) Linear regressions between the changes of the normal and tangential force in both frictional conditions (natural and talcum) and both directions of the force changes. The slopes are slightly different when talcum is applied (red dots) for both the decreasing and increasing normal force. (b) Values of the slopes across participants (individual values and mean ± s.d.) for the four experimental conditions. The lines connect the values recorded from the same participant.

III. Results

A. Contact forces

The average pre-modulation contact forces were computed by averaging their intensity across the 200 ms interval prior the start of the normal force modulation. The pre-modulation normal force was kept constant at 1 ± 0.01 N (Fig. 3a), while the tangential force changed significantly from the natural fingerpad condition to the talcum powder condition (Fig. 3b) (Wilcoxon matched-pairs signed-rank test: n = 10, W = 55, p = 0.002) with an averaged median intensity of 0.69 N (IQR = 0.85 – 0.62) and 0.43 N (IQR = 0.44 – 0.39), respectively.

We then measured the changes of the normal force induced by the platform. The change in force was obtained by computing the ratio between its value at the peak of the modulation and its pre-modulation value. The changes in NF generated by the platform did not depend on the application of talcum powder on the fingertip (Fig. 3c), but the actual amplitude of the change was found to be slightly larger than the predefined target value for the increased NF and slightly

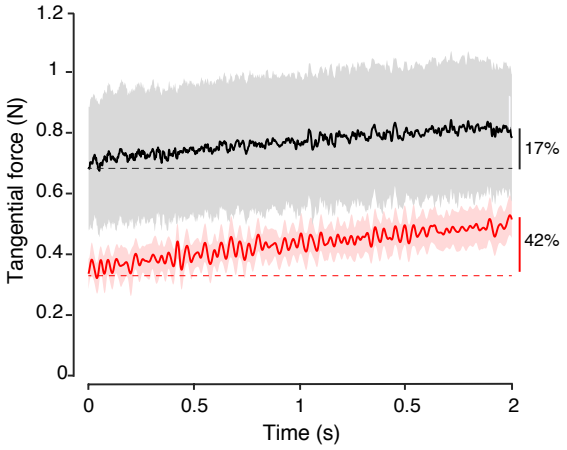

Fig. 5. Evolution of the mean tangential force across participants during the sliding with talcum (red) and without talcum (black). The normal force is kept constant at 1 N during the whole interval. The shaded error bars represent the standard deviation across participants. The total percentage of increase over the two seconds is reported on the right.

smaller for the decreased NF. This discrepancy is probably due to the mechanical properties of the robotic platform and the limits placed on its acceleration to avoid oscillatory motion. The later sections of this paper use the measured changes in the forces (rather than the commanded changes) to compute the psychometric functions and the corresponding contact mechanics.

B. Correlation between changes in the normal and tangential force

Since the tangential force is known to be influenced by the normal force applied on the material, we investigated how the modulation of the normal force (NF) impacted the tangential force (TF) exerted on the finger. To that end, we performed a correlation analysis between the changes in NF and the induced changes in TF for all experimental trials. We found the correlation to be strongly significant for the two frictional conditions (natural and talcum powder) and both decreasing and increasing force modulations (Pearson correlation statistics: $p < 0.0001$ for all four conditions) (Fig. 4a). In the range of our experiment, linear regression provided a good fit in both the natural and talc conditions. We could therefore compare the regression slopes for all four conditions (Fig. 4b).

Interestingly, a paired t-test showed that the slope of the linear regression in the natural condition was significantly different when the force decreased compared to when it increased ($tf = 11.71$, $df = 9$, $p < 0.0001$), with an average slope across participants of 0.78 and 0.62, respectively. With the talcum powder, the difference was not significant between the decreasing and increasing force conditions. Furthermore, we found that when NF was commanded to decrease, adding talcum powder significantly decreased the slope of the linear regression between the changes of NF and TF (Paired t-test: $t = 4.519$, $df = 9$, $p = 0.0014$). When NF was commanded to increase, the difference between the slopes with and without

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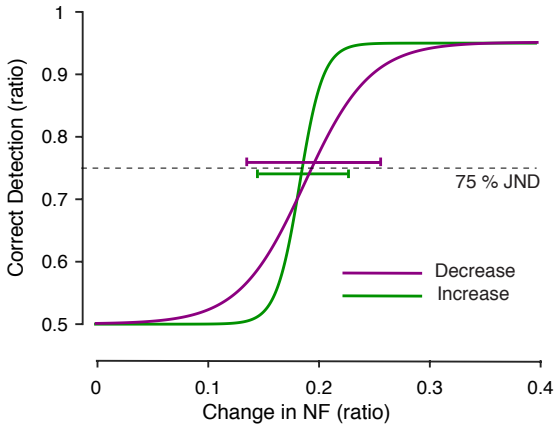

Fig. 6. In the natural state of the fingerpad, the psychometric function for the detection of the change, computed from the median of the individual slopes and thresholds (mean ± s.d. of the 75% JND) for both the decreasing NF (purple line) and the increasing NF (green line). A small vertical offset was introduced between the error bars to avoid overlapping.

talcum powder was not significant (Ratio paired t-test: t = 1.694, df = 9, p = 0.12). In that condition, rather than producing a consistent increase across participants, the application of talcum mainly reduced the inter-subject variability of the regression slope by reducing the large spread observed with the fingerpad in its natural state.

The regression lines at population level also showed a small positive offset in the y-axis of 0.03 without talc and 0.06 with talc, which suggests that the lateral force is slightly increasing even in the absence of change in NF, probably due to occlusion of the fingerpad. To quantify this phenomenon, we investigated the evolution of TF during the sliding in the catch trials, in which NF was kept constant. To that end, we computed the mean TF across all participants during the full sliding interval (except the initial 500 ms in order to avoid a border effect). The results confirmed that TF is continuously increasing during the sliding and that the total percentage of increase is larger for talcum: 42% vs. 17% (Fig. 5).

C. Human perception of changes in the contact forces

For the psychophysical task in the natural fingertip state, we used the mean change of NF in each condition to fit a psychometric function to the answers of each participant (Fig. 6). The 75% just noticeable differences (JNDs) for perceiving the brief decrease and increase were found to be ratios of 0.19 ± 0.06 and 0.18 ± 0.04, respectively. Thus, no perceptual difference was observed between perceiving a brief decrease or increase in the normal force. The slope of the psychometric function was found to be steeper when NF increases, but the effect was not significant (Wilcoxon matched pairs signed-rank test: W = 37, n = 10, p = 0.064).

Considering the strong induced change in TF, it is possible that the participants used TF as a proxy to perform the task. We tested this hypothesis by computing the 75% JND for both TF and NF in the natural fingertip condition and when talcum powder was applied. The 75% JND for the NF threshold remained the same when talcum powder was

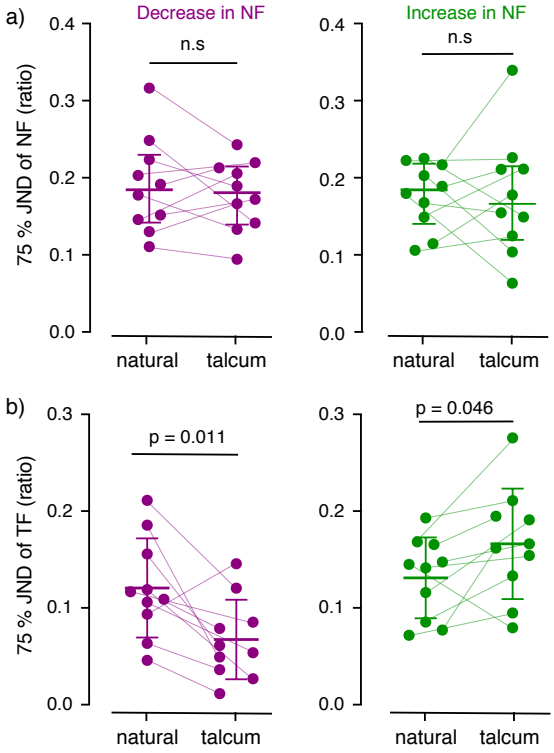

Fig. 7. (a) The 75% JND of the normal force (NF) changes in all the tested experimental conditions. The dots represent the individual values of participants. Purple and green are used for the decreasing and increasing NF condition, respectively. The lines connect the values recorded from the same participant. (b) The same plot for the tangential force (TF).

applied compared to the natural state of the finger in both force conditions (Fig. 7a). On the contrary, the 75% JND for the change in TF changed significantly with the addition of talcum powder (Fig. 7b). The TF threshold became smaller when NF briefly decreased (paired t-test: t = 3.203, df = 9, p = 0.011) and larger when NF briefly increased (paired t-test: t = 2.309, df = 9, p = 0.046). Importantly, the changes in the TF threshold were consistent with the modification of the correlation induced by the application of talcum powder.

D. Categorization of the changes

In addition to the detection of the modulated interval, participants were asked to report whether the normal force had decreased or increased. For all trials of a given condition in which the correct interval was reported, we computed each participant's ratio of correct categorizations about whether NF decreased or increased (Fig. 8). For the natural fingertip condition, participants categorized the correctly detected trials above chance only in the conditions with the largest decrease and increase in NF (Bonferroni corrected Wilcoxon signed-rank test with significance level at $p < 0.05$). When talcum powder was applied, an identical statistical analysis showed that the –0.3 and +0.3 N changes were also categorized above chance. Since the ratio of correct detections is similar with and without talcum, these results suggest a slight improvement in the human capacity to categorize when the

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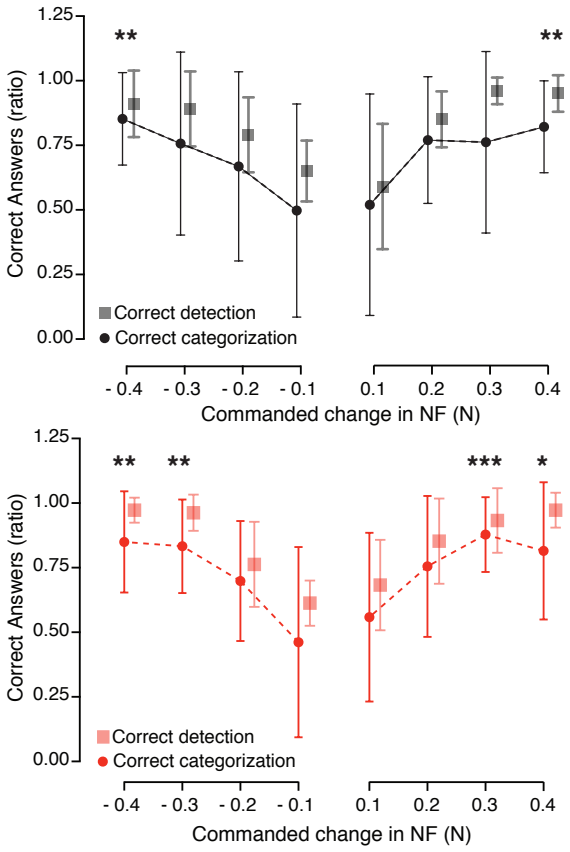

Fig. 8. The ratio of correct detection (mean ± s.d.) of a change in the normal force and the ratio of correct categorization (mean ± s.d.) of whether the normal force had decreased or increased for correctly detected trials. Both ratios are computed for all modulation levels during the experiment in the natural fingerpad state (black) and when talcum powder was applied (red). Categorization above chance level for a given stimulation level is marked with stars representing the significance level (*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$).

finger-surface friction is reduced by talcum powder.

IV. Discussion

The results of this study show that the correlation between the normal (NF) and tangential force (TF), which has been observed in gripping [22] and dynamic tactile exploration [16], is also valid when brief (500 ms) changes of NF are induced during passive sliding on a flat surface. Interestingly, the linear regression between the changes in TF and NF that we observed (0.78 when NF decreased and 0.62 when it decreased) is steeper than the measure for the same material (polypropylene) reported in [16], which is 0.29. This difference is probably due to distinct experimental conditions. The normal force in their experiments was changed only from one trial to the next, and the measurements that they used to compute the linear regression went up to 30 N. The steeper linear regression when NF decreases induced a smaller coefficient of dynamic friction (CF) for lower values of NF, contradicting the predictions of existing models [7]. However, the finger-surface friction needs several seconds to stabilize on a hard flat surface [23] like the one used in our experiment. Since we applied two transient changes of NF within 500 ms, the finger-surface friction probably did not have sufficient time to develop, which might explain the unexpected ratio between TF and NF.

We also found that TF was continuously increasing during the sliding motion. In the natural state of the fingerpad, a continuous increase of TF was expected since the skin of the fingerpad plasticizes when it is in prolonged contact with a flat surface. This phenomenon is provoked by the occlusion of the contact area, which retains the moisture produced by sweat in both dynamic [7], [23] and static touch [23].

The psychophysical results show that the perception of normal force modulation is approximately symmetric for decreasing and increasing changes and that its average Weber ratio, which is defined as the ratio of change that is detected in 75% of the trials, is around 0.19. These values are larger than the Weber ratio for perceiving changes in the tangential force, which was measured with a similar setup and estimated at 0.11 [24]. However, the stimulus rate of change in this study was constrained by the mechanical properties of the robotic platform; around 200 ms were needed to reach the peak values of NF. In studies focusing on tangential force, the peak value is usually achieved within a few milliseconds. These differences related to the rate of change might explain part of the difference in sensitivity. Indeed, it has been shown for electrostatic friction modulation that a smoother sinusoidal modulation is less likely to stimulate Pacinian mechanoreceptors than a sharp change [25], which are the tactile afferents with the lowest activation threshold during mechanical stimulation [26]. More generally, these thresholds are in accordance with those measured in the broader context of haptic perception [27].

Since the changes in NF induced changes in TF due to friction, TF was also available to the participants as a tactile cue. We used a low-friction condition obtained by applying talcum powder on the fingerpad to disambiguate between the two potential sensory cues. Adding talcum powder did not modify the NF threshold despite a significant change in the slope of the correlation between the changes in the two components. On the contrary, the sensory threshold for TF shifted in the same direction as the shift in the slope of the linear regression, which was opposite for the decreasing and increasing NF.

According to Weber's law, the 75% just noticeable difference of the parameter that is used for perception should be constant except for very low intensities, for which an increase in the perceptual threshold can occur [28]. In our study, after application of talcum, the TF threshold became smaller for the decreasing condition and slightly larger for the increasing condition. If participants had relied on TF, the TF threshold would have stayed constant or have become larger for both conditions. Thus, NF seems to be the main tactile cue that participants used to detect the interval.

When asked whether the force had decreased or increased, participants performed poorly even when they had correctly detected the change. The direction of the changing force was a second-order task following an already challenging detec-

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tion task. Nevertheless, it is still surprising how difficult this task was even when the stimulation level was far above their sensory threshold. We also found that participants slightly improved at this task with talcum on their fingerpad, which reduced the finger-surface friction. This finding points to a potential perceptual role of the tangential force component in the categorization of the type of force change. However, a task at which participants have better performance and larger disturbance of the frictional cues would be more informative about the respective contribution of NF and TF to the categorization of the type of change.

V. Conclusions

Overall, we performed a first evaluation of how humans perceive changes in the normal force between their finger and a smooth surface during passive dynamic touch, which also induced correlated changes in the tangential force. Participants consistently detected changes in normal force of 0.18–0.19 N compared to the 1 N reference. A control experiment with talcum powder suggested that subjects were mostly responding to changes in the normal force to detect the stimulus. However, reducing the finger-surface friction slightly improved their categorization of the change, which points to the possibility that both force cues mediated the perception of the changes.

In future experiments, we will use simultaneous ultrasonic vibration during the change in the normal force to decouple even further the two components of the force vector and create conditions of paradoxical changes in the two force components. Such an approach will enable us to study the interplay between the normal and frictional forces during dynamic tactile exploration in more detail.

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