Short Paper

Grip Force is Adjusted at a Level That Maintains an Upper Bound on Partial Slip Across Friction Conditions During Object Manipulation

Félicien Schiltz, Benoit P. Delhaye, Jean-Louis Thonnard, and Philippe Lefèvre

Abstract—**Dexterous manipulation of objects heavily relies on the feedback provided by the tactile afferents innervating the fingertips. Previous studies have suggested that humans might take advantage of partial slip, localized loss of grip between the skin and the object, to gauge the stability of a contact and react appropriately when it is compromised, that is, when slippage is about to happen. To test this hypothesis, we asked participants to perform point-to-point movements using a manipulandum. Through optical imaging, the device monitored partial slip at the contact interface, and at the same time, the forces exerted by the fingers. The level of friction of the contact material was changed every five trials. We found that the level of grip force was systematically adjusted to the level of friction, and thus partial slip was limited to an amount similar across friction conditions. We suggest that partial slip is a key signal for dexterous manipulation and that the grip force is regulated to continuously maintain an upper bound on partial slip across friction conditions.**

Index Terms—Friction, sensorimotor control, fingerpad mechanics, touch.

I. Introduction

Dexterous manipulation requires to constantly adjust the grip force level to the object properties (e.g., weight, friction) and kinematics (e.g., inertial forces). In particular, the tactile system collects information about the object-skin frictional condition, such that the grip force is adequately scaled to this parameter. Indeed, a slippery surface is squeezed more firmly than a sticky surface [7], [13], [23]. While tactile feedback is essential for a normal adjustment of the grip force [4], [24], it remains unclear what is the nature of the sensory feedback responsible for the force adjustment to friction.

When passively loaded tangentially against a flat surface, the finger slips in a progressive manner, such that the periphery of contact first loses the grip and then partial slips propagate to the center until full slip is observed [3], [10], [15], [21]. Partial slips are associated with substantial skin strains that are faithfully encoded by tactile afferents, suggesting that the central nervous system has access to at least some information about partial slip ([8], [9], [14]). Partial slip can also be readily observed during active manipulation, and the resulting skin strains are directly related to the grip force level [11]. Given the stereotyped pattern of deformation associated with partial slip, it can be a very salient feedback signal for the central nervous system, since it provides a mean to continuously gauge the stability of the contact. That is, the further partial slip propagates inside the contact area, the closer to full slip is the contact, or said differently, the more insecure is the grip. Indeed, we have also recently shown that following an unexpected reduction of friction, partial slip propagates further toward the center of contact and triggers quick grip adjustment [18].

Here, we asked whether grip force is continuously adjusted to maintain a similar upper bound on the level of partial slip. To that end, we asked healthy volunteers to perform point-to-point movements between targets while monitoring partial slip. Friction was changed every five trials. We found that while the amount of partial slip varied across participants, that is some participants manipulated the object with higher safety margin than others, most of them tended to manipulate the object to maintain a constant upper bound on the level of partial slip, thereby adjusting the grip force appropriately.

II. Material and Methods

A. Experimental Apparatus

We used a custom-made manipulandum with embedded optical imaging and intended to be held in a precision grip, i.e., between the thumb and the index fingers (Fig. 1A). The device is described in detail in another publication [11]. Succinctly, the forces applied by the index and the thumb were measured using two force sensors (ATI Mini27 Ti, ATI-IA, Apex, NC, USA). From those measurements, the grip force (GF) and the load force (LF and LFv) were computed (see *Signals and Strains Measurements*). The mass of the device was 540g and it was partially compensated with a counterweight of 320g, resulting in a static load force around 2.2N (apparent weight). An optical distance sensor (DT20-P224B) measured the vertical position of the manipulandum. The position and forces were sampled at 200Hz with a NI-DAQ card (NI3225, National Instruments).

The index fingerpad skin in contact with the glass was imaged using a custom optical system (Fig. 1D-E). This system uses the principle of frustrated total internal reflection which results in a high contrast between the parts of the skin in contact with the glass and those that are not, thus giving a detailed image of the fingerprint ridges. Images are recorded at 100 fps with a high-resolution camera (GO-5000M-PMCL, JAI, monochrome, 2560 x 2048 full pixel resolution). Image size is 1696 x 1248 pixels, which corresponds to an area of 26.5 x 19.5mm, with a resolution of 4096 pixel/mm^2. Those images enabled to monitor the partial slips (see below).

Two kinds of glass plates with different levels of friction were used. One of them was optically flat glass, and the other had a

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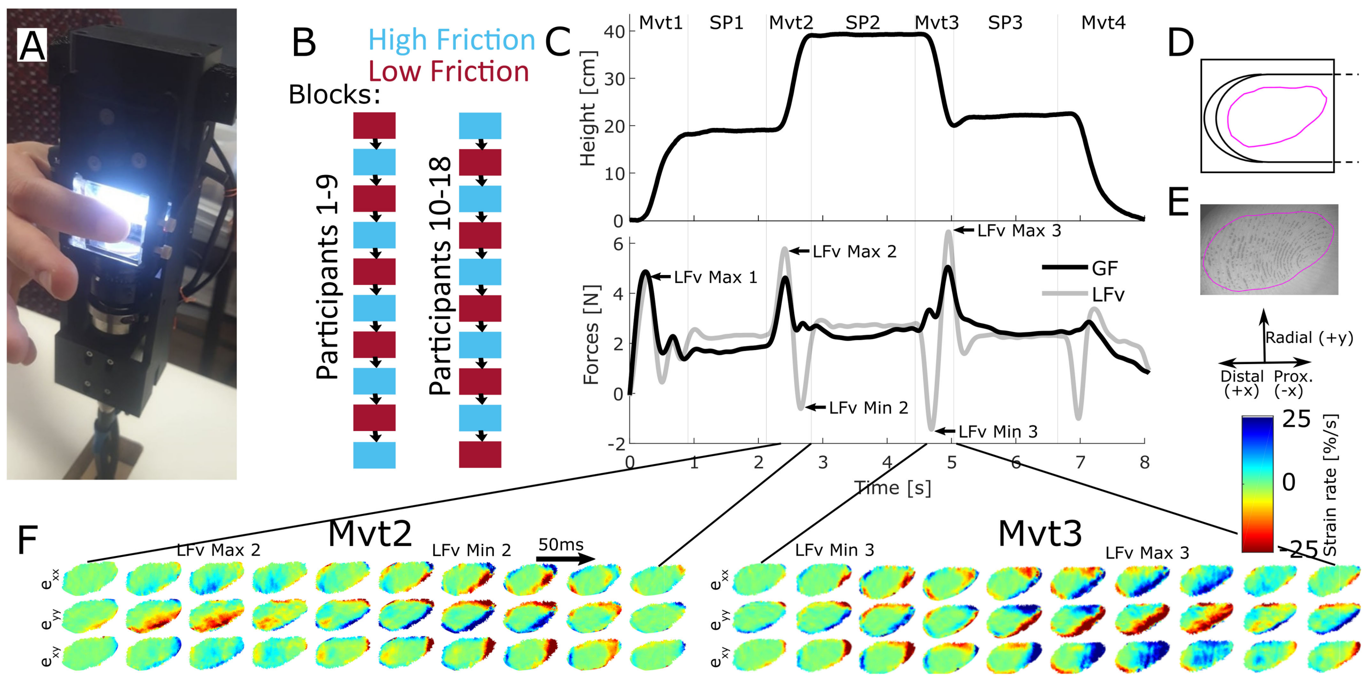

Fig. 1. Experimental setup, experimental procedure, and typical trial. A | The manipulandum, held in a precision grip. B | The friction was alternated after every block of five trials. Half of the participants started with each friction condition. C | Position and forces during a typical high friction trial, which consisted of a grip-lifting task followed by three point-to-point movements. Note that the weight of the device was partially compensated with a system of pulleys. D | Schematics of the position of the index finger relative to the reader for strain rates heat maps. E | Typical image of the fingertip obtained with the device. The delimitation area of contact is shown in purple. F | Typical strain rates during movement 2 and 3, corresponding to the typical trial in C. Blue corresponds to dilation and red to compression. The time of min and max LFv are indicated above the corresponding strain rates maps.

treatment such that it displayed roughness at the nanoscale level, changing the real area of contact between skin and the glass plate and thus reducing the coefficient of friction [2], [12], [20].

B. Experimental Procedure

Eighteen participants (5 females, ages 20-65), took part in the experiment. They all provided written informed consent to the procedure and the study was approved by the ethics committee at the host institution (UCLouvain, Brussels, Belgium). They stood in front of the table on which the device was standing. Each trial consisted of a grip-lifting task followed by three vertical point-to-point movements (one up and two down, see Fig. 1C), each of which had an amplitude of 20cm. The experimental procedures have already been described in greater details in a previous publication that analyzed the grip-lift movement only [18]. The procedures are therefore only summarized here. Auditory cues were used to pace each movement (0.8s) and pause between movements (1.5s). The glass plates of different friction were interchanged after each block of 5 trials (Fig. 1B). Half of the participants started the experiment with the high friction condition and the other half with the low friction condition. Participants were instructed to apply a minimal level of GF while still avoiding slippage of the device. Ten blocks of five trials were performed, for a total of fifty trials.

Note that a part of the data, namely the first lift of the object, is described in a separate study [18].

At the end of the experiment, the coefficient of friction was measured by using the method described in [5]. Briefly, participants rubbed their index and thumb back and forth on the glass plates at different levels of normal forces. The ratio of tangential force over normal force at the moment of slippage was used as an estimation of the coefficient of friction as a function of the normal force. The average of this function over the interval of manipulation (1-5N) was used as a scalar coefficient of friction value for each individual subject, as in Fig. 5. The measures of the coefficients of friction are provided in [18]. The coefficients of friction were different for each material-participant pair, but were consistently higher for one of the two materials for each participant. However, one participant was removed from the analyses because the friction measurements showed no difference between the two materials and two others because the quality of the images obtained did not allow precise measurements of strains. In the context of this study, we omitted trials 1 to 10 because learning had a large influence during those. We also omitted the first trial of each block to diminish the influence of the friction condition of the previous block.

C. Signals and Strains Measurements

Force and position data were collected with a sampling rate of 200Hz and filtered with a fourth-order low-pass Butterworth filter with a cut-off frequency of 40Hz. The Grip Force (GF) is defined as the mean of the norm of the forces normal to the surface of the object exerted by each finger. The Load Force (LF) is defined as the norm of the sum of the forces applied tangentially to the surfaces by each finger. LFv is defined as the sum of the vertical component of the forces applied by the fingers tangentially to the surface of contact. As the levels of GF were markedly different across participants, in some analyses, GF was normalized (i.e., Fig. 2), by dividing it by the average value of GF during the first static phase across all trials for each participant. Normalization values are provided in [18].

The images were collected at 100 fps. A previously described pipeline was used to measure the skin strains from the images [8], [10]. Briefly, the area of contact was semi-automatically detected using a custom machine-learning algorithm. Then, feature points were detected at the beginning, middle, and end of each movement and tracked forward and backward in time using an optical flow algorithm [16], [19]. A Delaunay triangulation was then computed and the evolution of the shape of the triangles was used to compute the local strain rate tensors, containing the two axial strain rates on the diagonal (horizontal, e_{xx}, and vertical, e_{yy}) and the shear strain rate (e_{xy}) off the diagonal. The norm of the tensor (e_n) was also computed as a measure of the amplitude of the strain no matter the orientation or the sign. In order to be able to combine strain data across participants (as in Fig. 4), we first projected the values of the strains from the triangulation on a standardized structured mesh common for all participants that took the form of an ellipse with a major to minor axis radii of 3/2. With all the data projected on a standard grid, we could then have an average of the strains rates norms for each participant in each condition and then compare those averages using t-tests (as in Fig. 4).

The stick ratio (SR) is the proportion of the finger contact that is not slipping on the glass. The value of the 90^{th} percentile of the strain rate norm used in Figs. 2, 3 and 6 has been described in a previous publication [11]. Briefly, it is a measure of the strain rate norm of the parts of the finger that undergo the largest deformation. The greater the deformations, the greater the value.

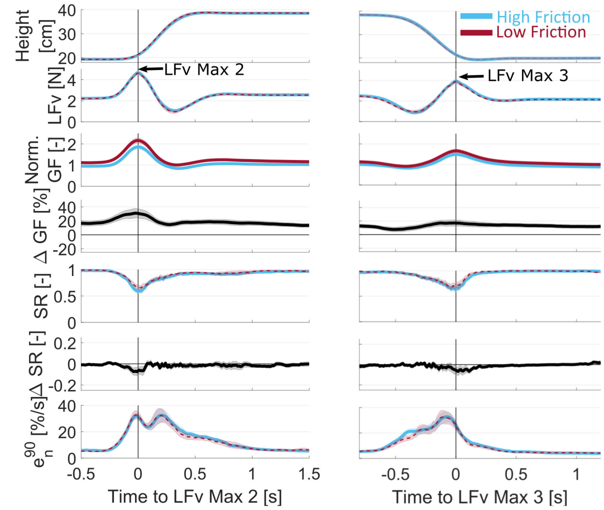

Fig. 2. Kinematics and dynamics during the second and third movements. Evolution of the manipulandum position (height), LFv, Normalized GF, difference of Normalized GF, SR, difference of SR and 90th percentile of the strain rate norm during the second movement for all participants (n = 15). Trials are synchronized at the time of LFv Max 2 (left) and LFv Max 3 (right). Shaded areas are standard errors of the mean.

III. Results

First, we describe typical strains rates patterns during point-to-point movements (Fig. 1). Next, we describe how the kinematics and the dynamics changed according to the friction condition and observe that the grip force adapted to the friction condition during movements and static phases. We also describe the evolution of the stick ratio (SR) and the amplitude of strain rates (Fig. 2). Next, we analyze the variables related to partial slip, such as the stick ratio and the amplitude of strain rates and we show that the grip force adjustment allowed to keep them unchanged despite the change in friction at the times of max LFv 2 and 3 (Fig. 3). After that, we compare the deformations according to the ratio of GF over LF and observe that when the ratio is lower, more deformation takes place (Fig. 4). Moreover, we map those differences of deformations. Then, we observe that participants with lower levels of friction show stronger adaptation (Fig. 5). Finally, we try to link the level of stick ratio to the adaptation of grip force from one movement to the next. No significant trend is observed (Fig. 6).

A. Typical Trial

The evolution of the device vertical position and forces applied by a participant during a typical trial are shown in Fig. 1C. The trial is divided into four movements and three static phases according to the kinematics during the trial. Movements 1 and 2 are upwards movements of 20cm while movements 3 and 4 are downwards movements of 20cm. Each movement is characterized by a positive and a negative peak of LFv. The first peak is related to the acceleration of the object, and the second is due to the participants having to slow down the device at the end of the motion, partly because of the counterweight and the resulting high inertia of the system.

The skin strain rates associated with movements 2 and 3 and corresponding to the trial in Fig. 1C are shown in Fig. 1F. The first rows (movements 2 and 3) correspond to the strain rates in the horizontal direction (along x), the second to the strains in the vertical direction (along y) and thus aligned with the movement, and the third correspond to the shearing strain rates. When looking at the vertical strain rates, we see that maxima of LFv are associated with compressions of the bottom part of the fingerpad while minima of LFv are associated with compressions of the top part of the fingerpad and dilation from the bottom part. As a consequence of the elastic properties of the skin, horizontal compressions take place in the parts where vertical dilations take place and vice-versa. Positive LFv peaks are associated with a larger amount of strains that go further into the contact area because of the higher value of LFv.

B. Kinematics, Dynamics and Fingerpad Mechanics During Movements 2 and 3

We have already established in a previous study that the level of friction is indeed different between the two glass plates, with an average relative difference of friction between conditions across participants in the interval 1-5N of 24%. We also showed that participants start adapting their GF to the new friction condition during the first movement of the first trial of each block [18]. We start by describing the kinematics and dynamics of the second and third movements according to the friction condition (Fig. 2). We can observe from the vertical position (Height) and LFv traces that participants performed very stereotyped movements and that the kinematics did not change across friction conditions. The Normalized GF and ΔGF curves show that participants squeezed the device harder in the low friction condition. This observation is valid for the static phases as well as during the movements. Note that those are expressed in terms of normalization values provided in [18]. It is interesting to note that the ΔGF increases and decreases with LFv, thus showing that participants modulated their GF with the LFv according to the level of friction. The difference in GF according to the level of friction was the largest at the times of maxima of LFv and thus at the times when the risk of slippage is the highest. Looking at the stick ratio (SR), we see that slippage progresses during the movement and peaks at the time of max LFv 2 and 3. The values of SR are similar in both friction conditions and follow similar profiles. The 90^{th} percentile of the strain rate norm follows a particular dynamic, where a double peak occurs for both movements 2 and 3. Again, the curves are very similar across friction conditions.

C. Mechanical Parameters Remain Stable Across Friction Conditions Thanks to Grip Force Adaptation

Looking at Fig. 2, we saw that participants adapt to friction by increasing their GF when it is more slippery, keep similar kinematics

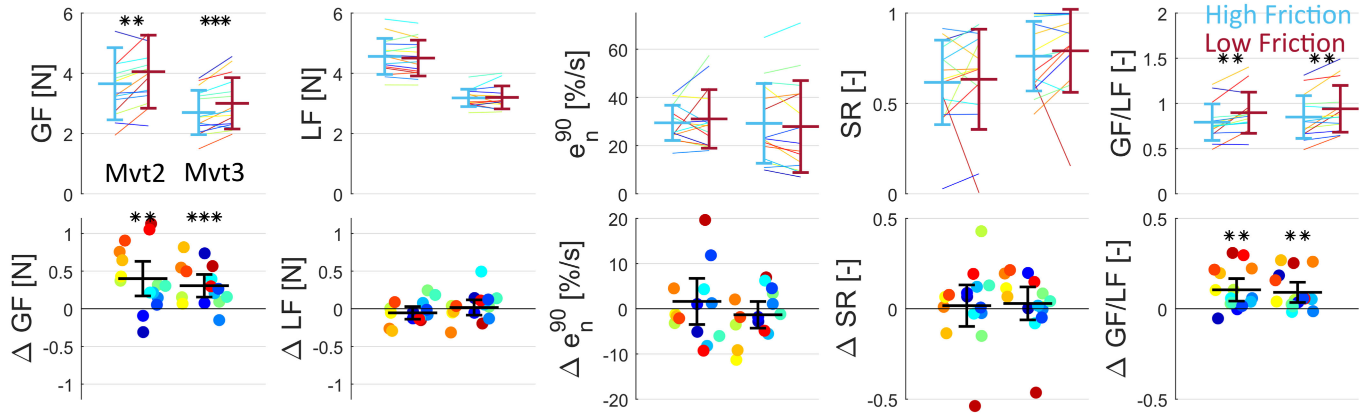

Fig. 3. Forces and mechanical parameters during the second and third movements. Values of the GF, LF, 90th percentile of strains rate norm, Stick Ratio, and GF/LF ratio at the time of the LFv max 2 and 3 (Mvt2 and Mvt3). In the first line, each point is the median value obtained for one participant across all trials of each friction condition. The error bars show the confidence intervals of the means. In the second line, each point is the paired difference of the Low Friction minus High Friction values of the first line. The colors of the points each correspond to one participant, going from blue to red, from the lowest difference of GF to the highest at LFv Max 2. The error bars on the left and right of each panel correspond to movement 2 and 3 respectively.

and that strains and SR levels remain very similar. In Fig. 3, we show the values of several variables of interest at the time of LFv Max 2 that describe the mechanics of the fingerpad as well as the forces applied. In the first row, each colored oblique line links the median value obtained for each participant across all trials. The second row is the difference of these median values between friction conditions for each participant. The colors of the individual points are each assigned to one participant and kept the same in all panels. They are classified from blue to red according to the ascending order of the values of ΔGF during movement 2. For movement 2 first, we observed that the GF differed across friction conditions (paired t-test, t(14) = -3.73.2, p = 0.0022) even though the levels of GF varied across participants. The levels of LF also varied across participants, remained constant across conditions (paired t-test, t(14) = 1.5, p = 0.18). This shows that participants did not tend to change their kinematics according to the friction condition. Similarly, we did not observe any statistically significant difference across friction conditions for the strain rates (e_n^{90}, 90th percentile of the strain rate norm) (paired t-test, t(14) = -0.68, p = 0.5) and for the Stick Ratio (paired t-test, t(14) = -0.32, p = 0.75). As could be predicted, the GF/LF ratio differed across friction conditions (paired t-test, t(14) = -3.6, p = 0.003). We can make similar observations for movement 3. Differences are observed for GF (paired t-test, t(14) = -4.36, p = 0.0007) and GF/LF (paired t-test, t(14) = -3.48, p = 0.004), but not for the LF (paired t-test, t(14) = -0.35,p = 0.73), the strain rate norm (e_n^{90}, paired t-test, t (14) = 0.97, p = 0.35) and the stick ratio (paired t-test, t(14) = -0.69, p = 0.5). We can thus observe that in both movements 2 and 3, when the friction changed, participants applied different levels of GF, which caused them to have similar levels of deformations and stick ratio while also keeping similar kinematics.

D. Amount of Strains Increases When GF/LF is Lower

Since we described the skin strain rates during movements 2 and 3 (Fig. 1F) and we showed that the difference in GF between friction conditions caused the level of deformations to remain relatively similar in Fig. 3, we investigated the effect of GF on the level of skin deformations. We compared the skin strains during movements 2 and 3, in Fig. 4A and 4B, respectively. In the first row, we look at high friction trials and the second, at low friction trials. The values reported are the differences in strain rate norm between the trials with a value of GF/LF higher than the median and those with a value lower than the median,

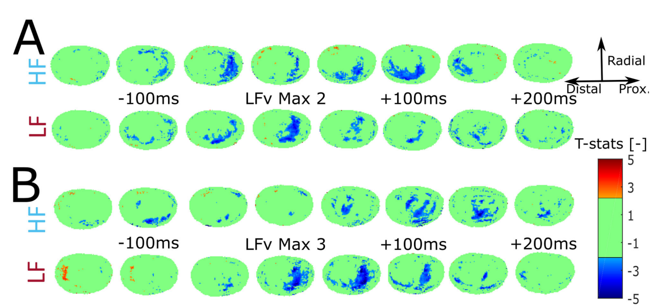

Fig. 4. Differences in skin strain rates according to the GF/LF ratio A | Heat maps of the t-statistics of the differences in strains rates between "high GF/LF" and "low GF/LF" trials during the second movement. The t-statistic is set to zero when the difference is not statistically significant and the corresponding p-value is larger than 0.05. The blue color indicates more deformations in the case of the "low GF/LF trials", the red color indicates more deformations in the case of the "high GF/LF trials" and the green no statistically significant difference. The first line is for the High Friction condition and the second for the Low Friction condition. B | Same as A, but for movement 3.

as expressed by the t-value obtained from t-tests performed for each point of the structured grid (see *Material and Methods)*. Intuitively, the blue patches show the parts where larger strains occur when GF/LF is lower, red patches where more strains occur when GF/LF is higher and green patches where the difference is not statistically significant.

First, we can observe in Fig. 4 that more strain takes place when GF/LF values are lower, as witnessed by the blue patches, which show the places where the finger deforms more in this case. Red patches are mostly absent, showing that when participants squeeze harder, there is almost no place in the fingerpad where more deformations take place. We can observe that the times when the largest differences in deformation take place are at the times of max LFv 2 and 3, as those are the times when there are the largest amounts of strains in general.

E. Participants With Lower Friction Show More Adaptation

Fig. 5 shows for each participant the value of the coefficient of friction as a function of the Adaptation Index. The Adaptation Index is defined as the difference in the normalized GF from the low to the high friction condition. We can observe from the left panel that participants who have lower coefficients of friction show larger adaptation (High Friction: $R^2 = 0.27$, p = 0.03, Low Friction: $R^2 = 0.3$, p = 0.02). This means that participants who have a higher risk of slippage overall tend to adapt to the friction condition more precisely.

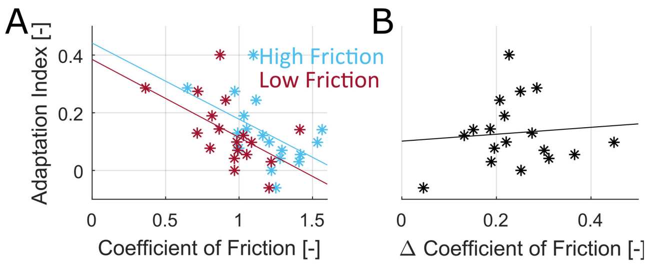

Fig. 5. Coefficient of friction and Adaptation Index. A | Values of the coefficient of friction in the high and low friction conditions as a function of the Adaptation Index. Values for the coefficient of friction are average values over the 1-5N interval of both fingers and the Adaptation Index is the difference in the normalized maxima of GF during movement 2. B | Same as A, but with the difference of coefficient of friction.

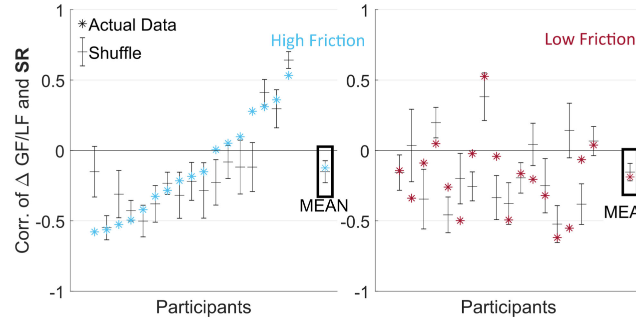

Fig. 6. Correlation between ΔGF/LF and SR The stars show the value of Pearson's linear correlation coefficient between ΔGF/LF and SR. ΔGF/LF is the difference between the values of GF/LF at LFvmax 2 and LFvmax 1. SR are taken at LFvmax 1. The boxes show the means across all participants. Error bars show the average and standard deviation for 1000 random permutations of the GF/LF of movement 2. For the means across participants, they show the standard error of the mean.

We can observe on the right panel that the difference of friction and the adaptation index were not correlated ($R^2 = 0.01$, $p = 0.7$).

F. Level of SR is not Linked to Adaptation of GF/LF From One Movement to the Next

So far, we have found that GF/LF levels were different according to the friction condition while the amounts of strains and Stick Ratio remained similar during movement (sections B and C) and that lower levels of GF/LF caused higher levels of strains inside individual movements (section D). Next, we sought to determine whether the Stick Ratio or the amount of strain observed during one movement (in this case, the first movement) could cause a participant to increase or decrease their GF in the next movement. Thus, we asked if these sensory signals can be used by participants to adjust the level of GF between trials. We tested the hypothesis whether when the Stick Ratio falls at a very low level at movement 1, it causes the subject to increase GF or slow down their movement 2. To that end, we measured the difference in the GF/LF ratio from movement 1 to movement 2. The GF/LF ratio was computed at the instants of peak LFv for each movement (this instant was chosen because it corresponds to the time when the chance of slippage is the highest). Then, we looked if this change was correlated with the SR observed in the first movement (as measured by Pearson's linear correlation coefficient). Note that we used the GF/LF ratio instead of the GF alone to account for the variations of the kinematics across movements. We found that indeed for most participants, those values were negatively correlated, as witnessed by most of the colored stars of both panels of Fig. 6 being below zero. Note that participants are ordered by ascending values of the coefficient of correlation in the left panel for clarity. This order is kept in the second panel so that the subjects can be identified across them. Most of the stars are below zero, suggesting that when SR was low during movement 1, participants tended to increase their GF/LF ratio for movement 2 and when SR was high, participants tended to decrease their GF/LF ratio for movement 2. However, for a given movement, GF and SR are also, by nature, correlated (lower GF is associated with lower SR). Therefore, our analysis is susceptible to spurious correlation. To test for such spurious effect, we shuffled the association between movement 1 and 2 across trials a thousand times, and recomputed the correlation (see shuffled data in Fig. 6). It can be seen in Fig. 6 that the error bars that result from the shuffling are generally also negative, showing similar levels of correlation, as indicated by the non-significant paired t-tests comparing the means of the shuffles and the actual data across participants (high friction, $t(16) = -0.59$, $p = 0.56$, low friction, $t(16) = 0.6$, $p = 0.53$). Thus, the effect shown in Fig. 6 might be due to spurious correlation and therefore our analysis does not demonstrate any evidence that GF was adjusted according to the level of SR in the previous movement.

The same analysis was made with e_n^{90} to see whether different levels of strain rates during movement 1 caused an adaptation of GF/LF between movement 1 and 2 (not shown here). These analyses yielded similar results. The correlations between e_n^{90} and ΔGF/LF were generally positive, but not greater than when movements were shuffled (paired t-tests, high friction, $t(16) = 0.16$, $p = 0.87$, low friction, $t(16) = -1.2$, $p = 0.22$).

IV. Discussion

In this study, we have shown that, by adjusting their level of grip force, participants kept similar lower bounds on the levels of stick ratio and strain rates across friction conditions. This is consistent with the observation made in [22] that participants adjust their GF to keep similar lower bounds on the Stick Ratio when lifting objects. It is also consistent with the observation that humans detect slippage based on the level of partial slip [6]. Given that single tactile afferents signal localized strain rates during partial slip [9], it is plausible that the stick ratio can be decoded at the population level [14] during active manipulation and that the central nervous system adjusts the grip force to keep this parameter above a lower bound.

The observation that participants who have a lower coefficient of friction tend to show a better adaptation to the friction condition (Fig. 5) might be anecdotic. However, it is not surprising since, given their low coefficient of friction, deformation of the skin will take place more easily, thus giving more information to the participant about the friction condition, as more afferents are activated. Moreover, the importance of adapting GF to the coefficient of friction will be higher for those participants, as the risk of slippage is also higher.

We have tried to assess whether the SR and the strains observed during a movement had an influence (corrective increase or decrease of GF) on the subsequent movement, but the data did not show any significant trend. The relationship between SR or the strain rates and the GF/LF ratio is not direct because several other factors, such as the position of the fingers on the glass, fingertip moisture that changes over time [1], [3], non-linear behavior of the skin [17] also play an important role. The changes in SR and strain rates in the present study that allow the adjustment of GF are much more minute since they are far from causing a full slip as the safety margin is not compromised and thus more difficult to observe when compared to the differences that took place after a change in friction as in [18].

V. Conclusion

We have shown that GF adaptation across friction conditions allows maintaining similar lower bounds on the levels of Stick Ratio and upper bounds on skin strain rates during manipulation. Future experiments should be conducted to try to get insight into the mechanisms that lead to online corrective GF adjustments.

Acknowledgments

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