

A Better Grasp on the Asymmetrical Adaptation of Grip Force in Response to Friction Perturbations

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Abstract—Our remarkable sense of touch provides us the feedback that is crucial for successfully manipulating a wide range of objects. The unconscious synergy between touch and the precision grip is particularly astonishing. During precision manipulation, humans constantly control their grip force to maintain a safety margin of approximately 25 percent above the minimum force required to prevent held objects from slipping. The ability to accurately control this safety margin heavily relies on tactile feedback founded on sensed deformations of our fingertips. Previous studies have demonstrated that, by using this feedback, humans even manage to maintain this safety margin independently of the weight or friction of a lifted object, and when the weight of a held object is perturbed. However, it is still unknown whether the sense of touch can help us to maintain this safety margin when the friction of a statically held object is perturbed. As previous methods could not deliver these friction perturbations, we demonstrated the viability of a new friction perturbation method that we employed to fill this knowledge gap. Here we show that humans in fact do not adapt their grip force in response to an abrupt increase of friction, but do increase their grip force in response to an abrupt decrease of friction. The asymmetry of these grip adaptations is consistent with current hypotheses on the limitations of our sense of friction. Our results support the existence of the hypothesized inability of our sense of touch to directly sense an increase of friction. These findings can help to enhance the haptic interaction between humans and machines, and may inspire the design of an artificial sense of touch that can greatly improve the manipulation dexterity of robotic grippers.

I. INTRODUCTION

EVERY single day, humans all around the world use their hands to successfully manipulate a large variety of objects with remarkable dexterity. Not one of these individuals, however, could give you a detailed explanation of what makes us so successful and dexterous at this skill. This disparity, between being able to successfully manipulate objects, but not knowing how, is not surprising, given that the control of this skill is largely driven by subconscious processes [1]. Partly due to this disparity, manipulation performed by a human hand, often remains far more dexterous today, than manipulation performed using any man-made device.

The dexterity gap becomes particularly evident, when analysing examples in which grips that rely on frictional forces are used to manipulate objects. Today, humans are, for instance, able to outperform even the most advanced robots when it comes to successfully manipulating chess pieces. Due to this ability, we are still capable of “defeating” these robots in a game of chess, despite the fact that chess engines are already capable of tactically defeating the best human players since 1997.

An example of a grip that relies on frictional forces and that is often used to manipulate chess pieces and many

other everyday objects, is the precision grip. Because of its prevalence in everyday object manipulation, this grip has been extensively studied, and will be the focus of this study. With the precision grip, the tips of the index finger and opposing thumb are used to load an object such that all forces acting on an object are balanced. This force balance restricts motion of the object relative to the hand, and ensures a stable grip on the object as can be seen in Figure 1. The force exerted by each finger can be resolved into two components: the applied grip force normal to the fingertip-object contacts (F_n), and the friction force that develops tangential to the contacts (F_f) due to the static friction (μ). All other forces acting on the object are typically summarized as the load force (F_l), and include the object’s weight and inertia, and any external forces acting on the object.

Humans typically control their grip force to always maintain a desired safety margin of around 10% to 40%, over the minimum grip force required to prevent the object from slipping through our fingers [1], [2]. This safety margin helps to restrict or even prevent undesired movement of a manipulated object during successful object manipulation. Humans control the magnitude of this safety margin with the goal of balancing effort, and the risk that the gripped object could slip [3].

Applying a safety margin to facilitate successful object manipulation may seem trivial, but how do we know how hard we should squeeze an object to achieve that safety margin? To answer that question, our sense of touch is of utmost importance. Skin deformation, sensed by mechanoreceptors that innervate the glabrous skin of the fingertips, form the foundation of the tactile feedback that is exploited in grip control [4]. From this feedback, and feedback originating from other sensory modalities, estimates of the load force F_l , grip force F_n , friction force F_f and friction itself μ , can often be faithfully and rapidly decoded. These estimates, in turn, allow us to effortlessly scale our grip force to maintain an appropriate safety margin, when lifting objects with various weights and friction properties [5]–[8]. When we are statically holding objects that are subjected to weight or load force perturbations, we are known to rapidly adapt our grip force to maintain a constant safety margin too [9]–[12]. Whether similar grip force adaptations also follow friction perturbations was, to the best of my knowledge, unknown before the current study was conducted.

The existence of this knowledge gap is not surprising, since perturbing the friction of a statically held object, is not as trivial as perturbing the load force by e.g. adding weight. However, friction at a fingertip-surface contact has been successfully reduced before through the employment of ultrasonic lubrication [13]. This phenomenon holds great

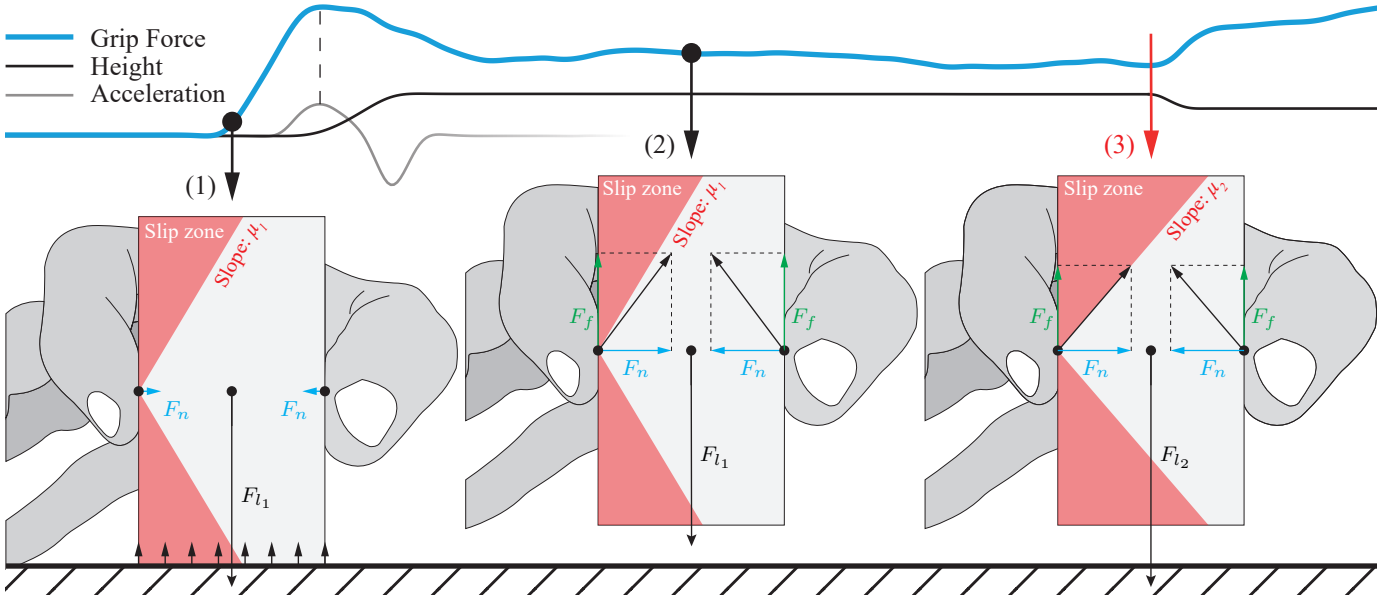


Fig. 1. This figure presents the forces acting on an object that is manipulated using the precision grip for three key stages of a lifting and holding task. For all stages, the slip zone for the index finger (red area), the load force F_l acting on the object, the grip force F_n (blue), and when applicable, the tangential force F_f (green), are drawn. The slope of the border of the slip zone is equal to the friction coefficient (μ_1) at the fingertips-object contacts. (1) The left configuration of the exerted forces correspond to the stage where the object is still supported by the ground and is initially contacted and squeezed before it is lifted of the ground. After this stage, the tangential (F_f) and normal (F_n) component of the finger forces are increased simultaneously in order to lift the object. The lift of the object is illustrated by the black trace of the object height on the top of the figure. The grip force (F_n) is coordinated to peak synchronously with the object acceleration peak, as illustrated by the dashed line. (2) After the object decelerated, the phase in which the object is statically held is reached. In this phase a constant safety margin between the finger forces and the slip zone border is maintained as illustrated in the central configuration of exerted forces. (3) The achieved static grip on the object is perturbed at the third and final stage. The load force is increased (F_{l2}) and the friction is reduced (μ_2), decreasing the slope of the slip zone in the process. The resulting exerted forces configuration is visualized at the right. Here the vectors of the finger forces required for balancing the load force (F_{l2}) can not exist outside their respective slip zones for the current grip force (F_n). As a result, the exerted finger forces will coincide with the borders of the slip zone, and the object will start to slip under the influence of unbalanced load force F_{l2} , as illustrated by the object height trace. A grip force (F_n) increase that stops the slip of the object is drawn.

potential for actively controlling the friction during any stage of a precision grip experiment. By ultrasonically vibrating a contacted surface, a squeeze film of air can be trapped at the fingertip-surface contact. This squeeze film effectively reduces the friction between the finger and the surface, much like the air ejected out of an air hockey table reduces the friction between the puck and the table.

In this study, this ultrasonic lubrication technique will be used to research the grip force adaptations that follow friction perturbations. Here, we do expect humans to adapt their grip force to maintain this constant safety margin in response to friction perturbations, provided that these perturbations are sensed. This expectation is in accordance with earlier discussed literature that learns us that humans attempt to control a constant safety margin. To test this hypothesis, we will perturb the friction between an object and the fingers used to lift and statically hold this object, while simultaneously measuring the grip forces applied on this object.

To allow the comparison of these new results, and the results presented in other precision grip study literature, we will attempt to replicate these existing results in the current study. Firstly, we will try to replicate the correlation between the scaling of the grip force coordination when lifting an object, and the friction at the object-fingertip interfaces [5]–[8]. In earlier studies, researchers obtained different frictional conditions between lifts by changing either the topography

of the gripped surface of the object or its treatment. In this study, participants will lift the object with either a neutral, or a reduced frictional condition that is obtained with the ultrasonic friction modulation technique. Here it is expected that the difference between these frictional conditions can indeed be sensed and that, as a result, the peak grip forces, the stable grip forces and, lastly, the peak grip force rates, will be higher for the reduced friction condition, as compared to for the neutral friction condition. Secondly, we will try to replicate grip force adaptations that follow load force perturbations [11], [12], [14] and also estimate grip force adaptations that follow combined friction and load force perturbations. These results are gathered to provide more context to any grip force responses that are observed to follow friction perturbations in this study. Following a perturbation, grip force is hypothesized to directly scale with the relative change of the minimum grip force required to hold the object, provided that this change is sensed.

We expect our results to contribute to our understanding of how, when and under which conditions we obtain a sense of friction. Furthermore, our findings could make way for a whole new line of manipulation studies in which ultrasonic lubrication is used to perturb friction and to further challenge our sense of friction and manipulation control.

II. MATERIALS AND METHODS

A. Participants

A total of 22 healthy handed participants participated in the experiment of this study. The participants were naive to the hypotheses posed in this study and all of them provided informed consent before participating in the experiment. The experimental procedure was approved by the ethics committee of the TU Delft. The dataset obtained in this study can be accessed via: <https://doi.org/10.4121/20217431.v1>.

In the default configuration of the experimental setup, the object (visualized in Figure 3) could only be easily manipulated using the right hand. As this configuration could not be easily changed and as the dominant hand needed to be used to manipulate the object, left handed participants were not invited to the experiment.

After the experiment, the data sets belonging to two participants were excluded from the results analysis. The data of the first of these two participants was excluded as this accidentally invited left-handed participant did not use his dominant hand when lifting and holding the object during the experiment. The data of the second participant was excluded as this participant could not complete the experiment due to a technical malfunction.

The average age of the 20 participants of which the data was included in the data analysis was 24.7 ± 2.3 years. 16 of these participants were male, and the other 4 female.

B. Setup

A drawing of the experimental setup used in this study is presented in Figure 2. As the experimental setup was not CE-certified, the setup was inspected by the safety manager of the 3me faculty of the TU Delft, and deemed safe to be used in interaction with humans. The main structure of the experimental setup consisted of 30x30 mm aluminium struts with 8 mm slots on each side (Bosch Rexroth, 3842990720/1000). All other components of the setup were assembled to this structure.

The weight of the held object was 293 g. The grip forces required to support this weight was, in combination with the typical friction at the interfaces between the object and the fingers holding the object, amply sufficient to allow the detection of slip at these interfaces [15], [16]

1) *Linear guide*: The held object was guided on a 8 mm steel shaft (Bosch Rexroth, R100000800,400mm) using two linear ball bearings (INA, KH08-B), as can be seen in Figure 3. The purpose of this guide was to counteract any torques that arise around the fingertip-object contacts. The maximal potential length of the projection of the arm between the center of mass of the object and the fingertip-object contacts on the plane parallel to the fingertip contacts, was relatively short. As a result, a relatively high grip force was required in order to achieve a frictional force large enough to balance the torques on the object. This required force was often much higher than the grip force required to prevent the object from vertically slipping. Therefore, the object was often found to easily rotate around the axes parallel to the fingertip-object interfaces.

Since the goal of this study was to investigate the grip force participants employed to prevent the object from vertically

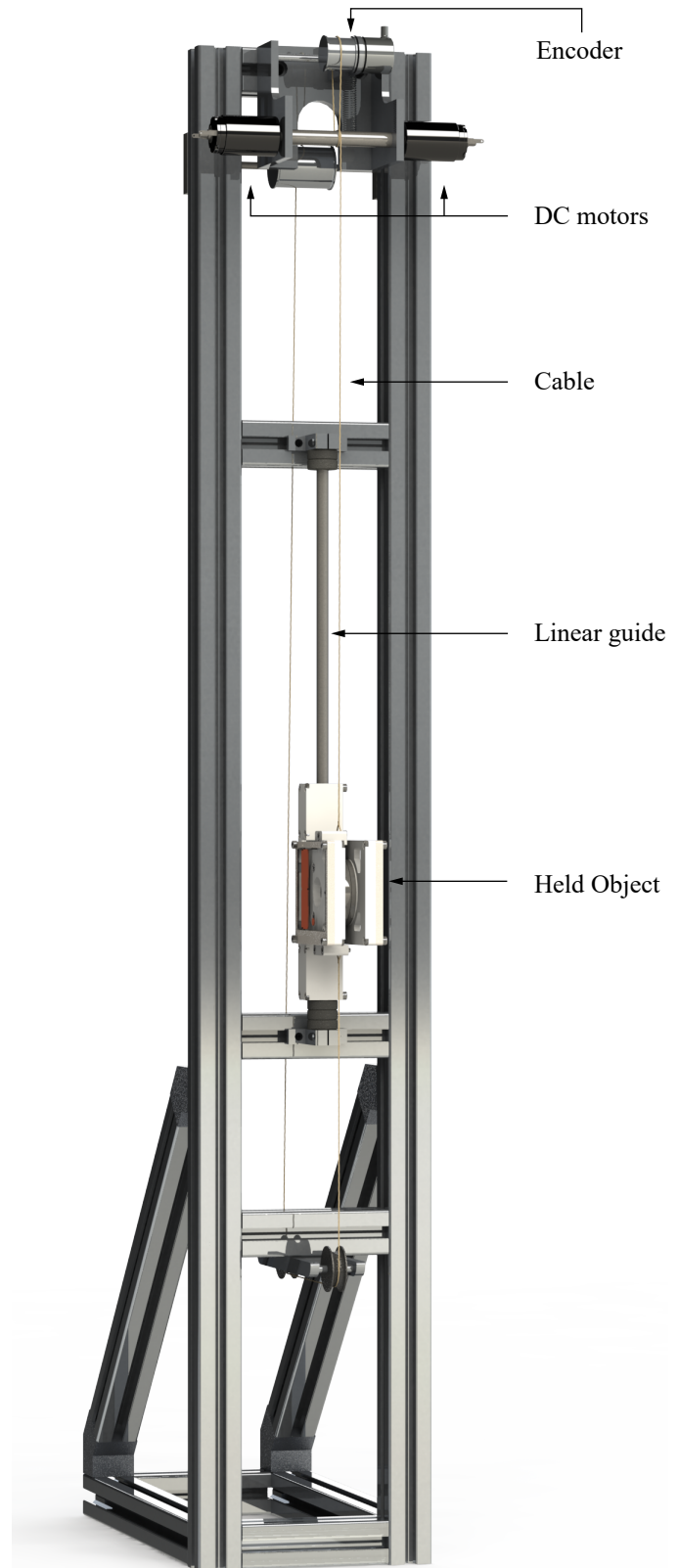


Fig. 2. A render of the experimental setup that was employed in this study. The most essential components of the setup are pointed out. A zoomed in exploded view of the held object can be found in Figure 3. The held object was free to move along and around the linear guide.

slipping, rather than preventing rotation of the object, the guide was added to counteract any torques that otherwise had to be counteracted by frictional forces at the fingertip-object interfaces. However, a balance between the normal force applied by both fingers was still desired. Thus, a fully circular shaped shaft was employed as linear guide in order to permit rotation of the object around the guide. The circular shape prevented a participant from applying different normal force levels with each finger, as such force imbalance would result in rotation of the object around the shaft.

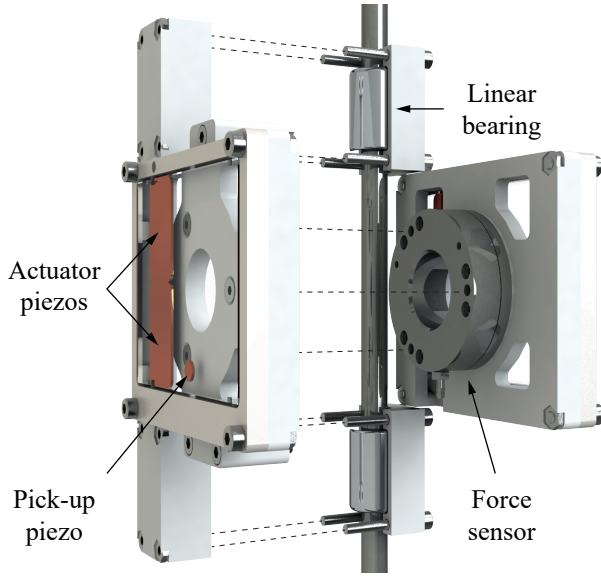


Fig. 3. An exploded view render of the object that had to be manipulated during the experiments. The dashed lines in this figure illustrate the screw-threaded hole connections that normally connect the two sides of the object which are presented in this exploded view. Figure 2 illustrates how this object was assembled to the experimental setup.

2) *Data acquisition:* All measurements were acquired using two data acquisition boards (DAQ) that were synchronized using a start trigger, resulting in a start delay of $0.35 \pm 2.8 \mu s$. The DAQ, which we will refer to as the first DAQ (National Instruments, NI 6351), was on the receiving end of the trigger for practical reasons, whereas the DAQ, which we will refer to as the second DAQ (National Instruments, NI 6351), was responsible for producing the trigger. Besides acquiring measurements, the first DAQ also controlled the load force and friction perturbations using two analogue outputs.

The sampling rate of the first DAQ was set to 250 kHz, which was the maximum rate possible with the amount of analog inputs acquired in this experiment. At this rate, the amplitude of the ~ 30 kHz inputs to this DAQ could be sampled confidently. The sampling rate of the second DAQ was set to an eight times lower rate of 31.25 kHz. However, as this high sampling rate was not particularly beneficial and, therefore, resulted in unnecessary long processing times, raw measurements acquired with this DAQ were, after the experiment had concluded, down sampled to obtain data with a sampling rate of 50 Hz. This rate ensured that time points sampled by the second DAQ were synchronized with some of the time points sampled by the first DAQ.

3) *Load force perturbations:* The apparent weight of the held object could be manipulated by pulling the object in the direction of the gravitational field using two DC motors (Faulhaber, 2642 012 CR). The torque delivered by the DC motors was converted to a pulling force by means of a cable wound on an axle that was assembled to the motors (illustrated in Figure 2). This cable was connected to the top and bottom of the held object in order to deliver a force in the direction of the gravitational field. The pulling force produced by the DC motors could be controlled by regulating the current fed to the motors using a servo amplifier (maxon, LSC 30/2). The current output of this servo amplifier was set by one of the two analogue outputs of the first DAQ. The load force perturbation levels used during the experiments were -0.5, 0 and 0.5 N.

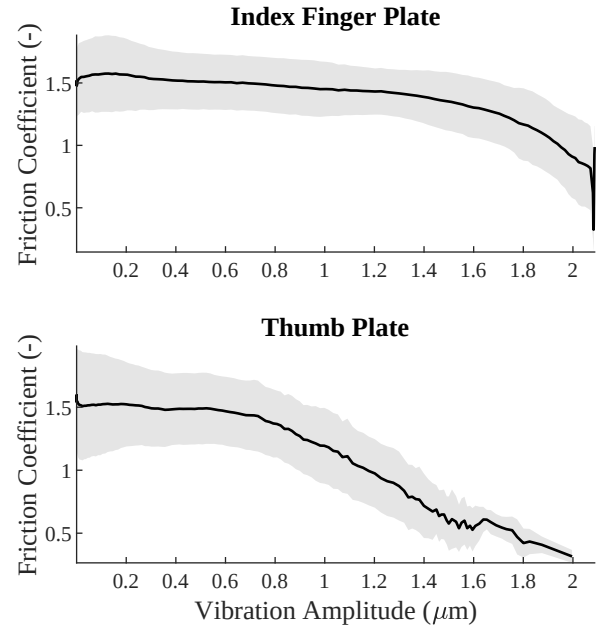


Fig. 4. ($N=1$) This figure presents how the dynamic friction between a finger of one participant and the antinode of the two friction modulation plates employed in this study decreased as function of the local vibration amplitude. The solid lines correspond to the mean of the friction coefficient estimated for a vibration amplitude, whereas the shades correspond to their standard deviation. The friction was estimated by multiplying the tangential force and the inverse of the normal force that were applied by a sliding finger. The normal force was maintained at ~ 1 N during these measurements.

4) *Friction perturbations:* By exciting a vibration mode of the glass object surfaces, the global friction at a contact between these surfaces and a fingertip could be decreased as illustrated in Figure 4. As a result, the highest friction reduction can be found at the antinodes of the excited vibration mode, as the spatial friction reduction map follows a trend similar to the excited vibration mode amplitude map.

During the design of the friction modulation plates, the goal was to excite mode 3-0 (illustrated in Figure 5) at an ultrasonic frequency to prevent auditory nuisances. The shape of this mode allowed us to achieve a friction reduction which did not depend on the vertical positioning of a finger, making the friction reduction magnitude robust to vertical slips that might occur at the object-fingertip interfaces during a trial.

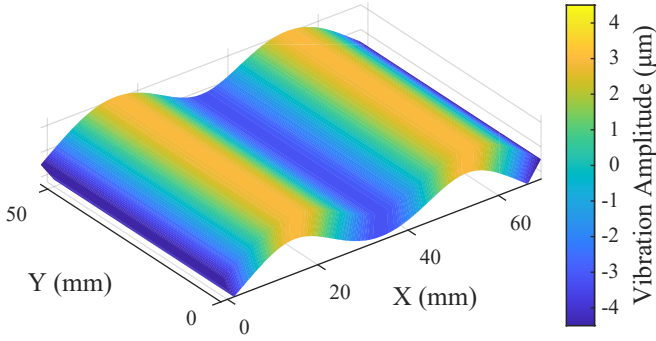


Fig. 5. A visualisation of the 3-0 mode shape of the glass friction modulation plates at the excitation frequency of ~ 30 kHz. In this figure, the ratio between the vibration deformation amplitudes and the plate dimensions are highly exaggerated for illustrative purposes. The indicated vibration deformation amplitude is the typical amplitude that was achieved when no fingers are placed on the plate.

Since the potential friction reduction is speculated to be strongly related to the vibration displacement amplitude, [13] and the gain of this amplitude typically decreases for higher resonance frequencies, the mode excitation frequency should be barely ultrasonic in order to optimize the potential friction reduction while preventing auditory nuisances. For similar reasons, the friction modulation plates were designed to be relatively thick as increasing plate thickness reduces the vibration amplitude attenuation introduced by the damping of a contacting finger. Free boundary conditions were modelled while simulating the resonance frequency of mode 3-0 for various plate dimensions, as these boundary conditions allowed for the highest vibration amplitude gain. In practise, these free boundary conditions were approached by fixing the plates at the ends of the first and fourth nodal lines using nylon M2 cheesehead screws (RS PRO, 527-909). Fixing the plates there did constrain displacement and rotation at only these nodal points. The displacement constraint had little impact on the dynamics of the mode as nodal points would remain stationary regardless. The rotational constraint did diminish the freedom of the boundary conditions slightly as the rotational stiffness of the screws and the friction between the screws and the plates imposed a relatively mild constraint on the rotation of the fixed points. Eventually, all these considerations resulted in the dimensions of the friction modulation plate designs being set to $68 \times 52 \times 5$ mm³, in order to achieve a high potential friction reduction when exciting mode 3-0 at an ultrasonic frequency.

Each friction modulation plate was actuated by an array of two piezoelectric actuators (STEMINC, SMPL-26W16T07111). Using epoxy adhesive (3M, Epoxy Adhesive DP490), these actuators were glued around a side antinode of the 3-0 mode and on the non-contacted side of the surface, as illustrated in Figure 3. The signals driving the actuators were generated by a function generator with two separate channels (Tektronix, AFG1062) and subsequently amplified by two power amplifiers (PiezoDrive, PD200). Before running experiments, the frequencies of the driving signals were set to the resonance frequency which corresponded to mode 3-0. This selection procedure always resulted in a driving frequency

of roughly 30 kHz. However, slight adjustments to the driving frequencies were sometimes necessary to compensate for resonance frequency shifts, caused by plate dynamics changing in between experiments.

The amplitude of the driving signals were chosen to maximize the vibration mode amplitude and the corresponding friction reduction, while preventing heating at the interfaces between friction modulation plates and fingertips throughout the experiment. The mechanics underlying this heating are not fully understood yet. The heating did seem to hold a strong relation to the vibration amplitude at a contact between a friction modulation plates and a fingertip and was argued to originate from kinetic energy being dissipated into thermal energy at the contact. This theory is supported by the large decrease of the desired vibration mode gain that occurs when the antinode of this vibration mode is damped by a finger ($\sim 45\%$ for 1 N normal force). This decrease and the heat generation scaled with increasing normal forces at the contact. By limiting the driving signal amplitude and, consequently, the kinetic energy of the friction modulation plate, painful and often noticeable heating at the contact could be prevented for typical maximal normal forces applied when the plates were driven (5.91 ± 2.44 N).

The voltage amplitude of the signal used to drive the plate was set to 25 V for the plate that was gripped by the index finger and to 20 V for the plate that was gripped by the thumb. This resulted in a undamped maximal settled vibration amplitude of 4.6 ± 0.17 μm for the index finger plate and 4.5 ± 0.15 μm for the thumb plate. When the plates were gripped, the maximal settled vibration amplitude was 0.97 ± 0.43 μm for the index finger plate and 1.0 ± 0.52 μm for the thumb plate.

5) *Measurements:* During the experiment, forces enacted on the object were measured using a 6-axis force and torque sensor (ATI, Nano43). These measurements were subsequently acquired by the second DAQ. Measurements on the vertical position of the object, made by an incremental encoder (Baumer, BTIV 24S 16.24K 1024 G4 5), were acquired using the same DAQ.

The first DAQ was used to acquire the monitor outputs of both piezo amplifiers, which correspond to the signals used to drive the friction modulation plates, amplified by a factor 1/20. Two additional signals, acquired by the first DAQ, served to estimate the deformation of both friction modulation plates. These signals contained measurements on the curvature at an antinode of the expected excited mode shape, taken by a piezoelectric sensor (STEMINC, SMD05T04R111WL) on each friction modulation plate. The placement of these piezoelectric sensors is illustrated in Figure 3.

C. Experimental protocol

The full experimental protocol, including reception, instructions and consent provision, took under an hour to complete. The experimental phase spanned a total of 48 trials, and lasted $27:17 \pm 3:46$ minutes. Each trial, the participants were asked to casually lift, hold and replace an object using the tips of their index finger and opposing thumb of their right hand.

While gripping and holding the object, the objective was to limit the contact with the object's surfaces to their vertical centre lines. There, the potential friction reduction was the greatest as discussed in [subsubsection II-B4](#). Furthermore, the participants were instructed to refrain from spending more effort, both mentally as well as physically, than they would spend when casually gripping everyday objects.

The experiment comprised 2 sequential phases: a familiarisation phase lasting 12 trials, and a testing phase lasting the 36 remaining trials. During the familiarisation phase, participants had the opportunity to practise and learn the task. Furthermore, the researcher provided participants with feedback on their finger placement in the course of this phase. As the between trial variance introduced by adaptation in the familiarisation phase was considered to large, solely data gathered during the testing phase is analysed to answer research questions posed in this study. Adaptation effects that occurred during the familiarization and testing phase are presented and analysed in [section B](#).

Participants were offered a break every 15 minutes. In addition, they had the opportunity to request a break in between trials. Breaks were primarily intended to prevent muscle fatigue but were also used to discuss anything that was unclear. Participants received an auditory notification as soon as a trial was paused. During a pause, any active friction or load force perturbations were deactivated to prevent overheating and wearing the hardware. Any measurements acquired before a pause, were overwritten by new measurements as soon as a paused trial was resumed and restarted. The last completed trial could be restarted as well. This function was useful for whenever a participant failed to stick to a trial protocol, but did complete the trial. For example, when a participant failed to hold the object at the glass surfaces throughout a trial. A trial restart could be requested by the participant or offered by the researcher. If necessary, multiple last completed trials could be restarted to redo any completed trial including subsequently completed trials.

In order to prevent the influence of auditory cues produced by the experimental setup whilst perturbing the load force, friction or both, participants wore passive noise-cancelling headphones (3M, HRXS220A) providing audio. The provided audio consisted of experiment instructions and audio to the episode "From Deserts to Grasslands" of the nature documentary series "Our Planet". Participants had the opportunity to watch this documentary throughout the experiment in order to spend excess mental capacity whenever desired. This opportunity to spend excess mental capacity was found to prevent boredom and to greatly improve the comfort of the experiment. Furthermore, it was offered to the participants to make it easier to approach each trial as if it was a typical everyday manipulation task. The control processes active during these kind of tasks, usually operate principally subconsciously [1], [17]. During pilot experiments and without the opportunity to watch a nature documentary as primary task, participants could not be helped to wonder and focus on what was happening to the object throughout the experiment, resulting in an atypical manipulation task and presumably an increased number of conscious grip control interventions. In order to quantify the

amount of mental capacity participants spend on watching the nature documentary during the experiment, the last 18 participants that were included in the results analysis were unexpectedly quizzed on the nature documentary after the experiment had concluded (see [section A](#) for questions). It was found that, in general, participants took the opportunity to spend excess mental capacity as they answered 3.00 ± 1.03 out of the 5 questions on details in the documentary correctly.

D. Trial protocol

Each trial can be broken down into two phases, a lifting and a holding phase. Participants encountered two different conditions in the lifting phase, an ultrasonically reduced and a neutral friction condition. For these two conditions the friction modulation plates were respectively not actuated, or driven by the signals that were discussed in [subsubsection II-B4](#). During the holding phase participants encountered nine different perturbation conditions in which the load force and friction were either decreased, kept constant or increased. However, since the friction modulation level was only changed between on or off or kept constant during the holding phase, only six of those perturbation conditions could be presented per preceding friction condition.

Therefore, the combination of the initial friction and perturbation conditions resulted in a total of twelve unique trial conditions. All these unique trial conditions were presented once during the familiarisation phase and thrice in the testing phase. The order in which these conditions occurred was randomized. Whenever a trial was restarted, the order of the remaining conditions was shuffled to prevent foreknowledge on the upcoming trial condition.

1) *Lifting phase:* The start of the lifting phase was cued to the participant using a single beep, right after the measurements and friction condition for this phase were initiated. Following this beep, the participant was expected to grip and lift the object with their dominant hand. They were instructed to lift the object to a preferred height where the movement of the object was not blocked by any of the linear guide's end stops. Before continuing to the holding phase, the participant's grip on the object was required to settle sufficiently first.

Such settled grip ensured low random grip force variance and, as a result, a good contrast between potential grip force adaptations and other sources of grip force variance. The participant's grip was determined to be settled sufficiently when two metrics, velocity and grip force variance per second, were below corresponding thresholds. Secondly, the grip force applied by the participant needed to be in between a lower and upper bound in order to progress to the holding phase. The lower bound was implemented to make sure the object was gripped in the first place, the upper bound to prevent excessive grip forces. When grip force exceeded the upper bound and the object was considered stationary according to the velocity threshold, an "ouch" sound played to warn participants to reduce their grip force.

The first purpose of this feedback was to make sure the potential friction perturbation magnitude, which decreases with increasing normal forces as discussed in [subsubsection II-B4](#),

remained relatively high when advancing to the holding phase. The second purpose was to stimulate efficient grip control by discouraging the typical initial cautious grip control caused by the fear of dropping and breaking the held object.

In order to check whether all criteria for terminating the lifting phase had been met, the time averages of the various metrics were computed from newly acquired measurements every half second. Subsequently, it was checked whether these time averages passed all their corresponding thresholds. By default, the pass range for the grip force was $0.2 - 5$ N and the upper bound on the velocity and grip force variance respectively $1 \cdot 10^{-3}$ N/s and $5 \cdot 10^{-3}$ m/s.

At times, the upper bounds on the grip force and its variance were observed to be too low to fulfil their purpose effectively. Some participants sporadically surpassed the default upper bound on grip force when applying efficient grip force levels for instance. Reducing their grip force to levels below the upper bound could in these cases even result in slippage. Furthermore, typical settled grip force variance levels of participants were occasionally too high to reliably satisfy its corresponding default threshold for instance. During the familiarisation phase, these too low upper bounds were adjusted to mitigate negative consequences. Throughout the testing phase these values were subsequently kept constant to avoid introducing variance in the data.

Unfortunately, the processing of the force measurements on which some metrics for terminating the lifting phase and for the "ouch" feedback were based was flawed for the first twelve participants that were included in the results analysis. For these participants, the various grip force dependent thresholds were adequately adjusted to roughly fulfill their purpose. However, while the derived force values did linearly correlate with the actual force values when the friction modulation plates were gripped at the same position, this relation disappeared when the plates were gripped at different positions. As a result, these participants occasionally received incorrect feedback on the magnitude of their grip force.

While I expect that this flaw certainly affected the results obtained in this study, I do not expect that its influence benefited the hypothesis. In fact, I expect that it may have benefited the null hypothesis for the lifting phase. The sensation of partial squeeze films might have moved the participants to grip the object off the vertical center line for the reduced friction condition. This finger placement was found to increase the magnitudes of the flawed grip force estimations. Therefore, the first 12 participants might have received "ouch" feedback for lower actual grip force values when the initial friction condition was reduced.

2) *Holding phase:* After completing the lifting phase, the measurement session initiated at the start of this phase was stopped for technical reasons. The initial friction condition was maintained however. A new measurement session was initiated as soon as possible, following the termination of the lifting phase measurement session. The inputs required for executing the perturbation condition were queued simultaneously, marking the start of the holding phase. The measurement discontinuity during trials (illustrated in Figure 6), lasted 1.24 ± 0.2 s. No data was acquired during this time.

The holding phase lasted exactly 10 seconds. To limit predictive grip responses in anticipation of a perturbation, the start of the holding phase was not cued to the participant. During the first two seconds, the initial friction condition was maintained in order to facilitate an accurate estimation of the grip force baseline. After these two seconds, the participant's grip on the object was perturbed according to the perturbation condition of the trial. Both the load force and the friction modulation signal amplitude changes were ramped in 0.05 s. In the remaining eight seconds, the perturbation was maintained and the acquirement of measurements continued in order to be able to record both rapid and relatively slower grip force adaptations.

At the end of these eight seconds, the trial ended and the measurement session stopped, while the perturbation was still maintained. The participants were informed on the end of a trial by a double beep. Following this double beep, participants were expected to return and release the held object. Meanwhile, all data acquired during the two measurement sessions was saved. After the data was successfully saved, a new measurement session was started to check whether the participant released the object before continuing the experiment. While the protocol for this check was similar to the settled grip check performed earlier in the trial, the criteria were naturally different. To pass this check, only the grip force was required to be below 0.2 N. When the check was completed, the perturbation was removed and the next trial started. However, if the completed trial was the last trial and the trial did not need to be redone, the experiment was concluded.

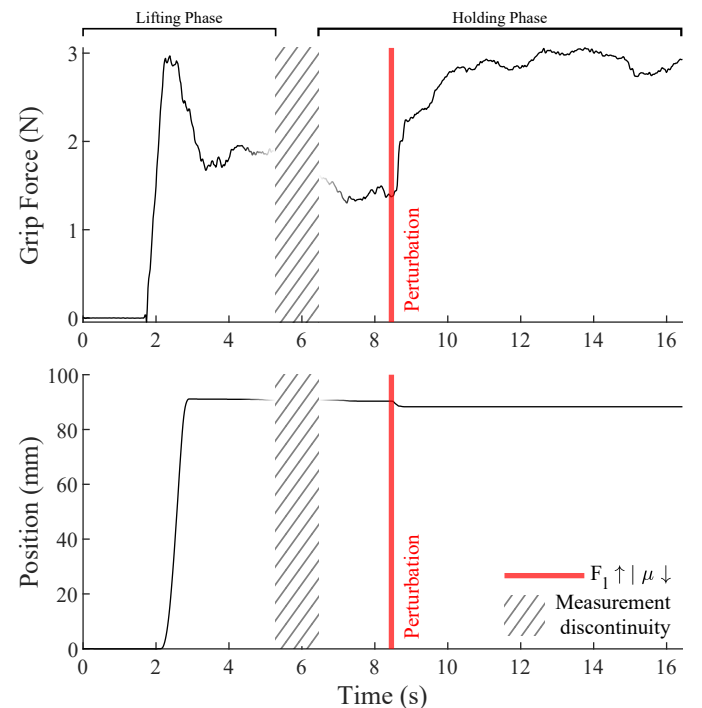


Fig. 6. This figure presents the grip force and vertical position measured during a sample trial. The measurement discontinuity between the lifting and holding phase measurements is illustrated by the grey slanted lines. The initial friction for this trial was neutral. The perturbation applied during this trial was a mix of a load force increase and a friction decrease. It was applied at 2 seconds after the start of the holding phase.

E. Data processing

The position of the manipulated object alongside the grip force applied on the object during a typical trial, are, as a function of time, presented in Figure 6. The initial friction in this trial was neutral, whereas the perturbations presented to the participant included a load force increase and a friction decrease. This section will explain and visualize how the measurements that were acquired during the lifting phase of a single trial are processed to allow the meaningful combining of all lifting phase data.

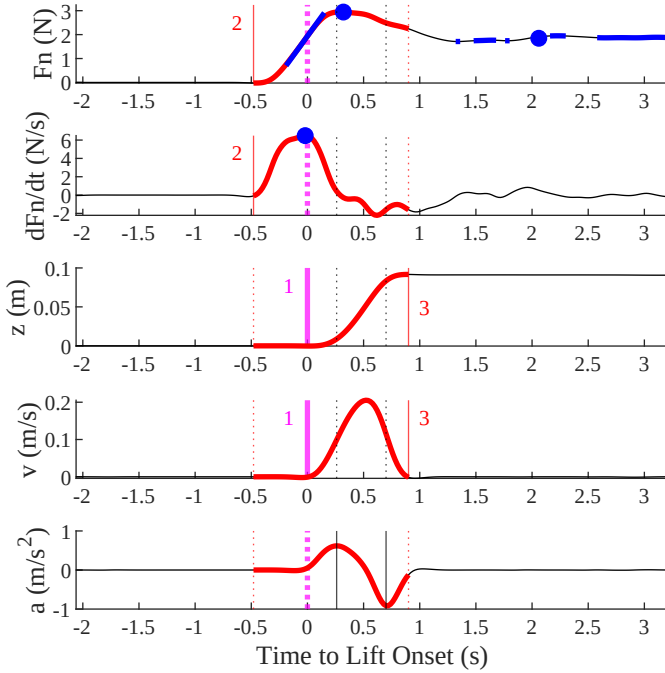


Fig. 7. This figure presents the filtered measurements that are obtained during the lifting phase of the sample trial (Figure 6). Some of the time derivatives of these filtered measurements are included as well. From top to bottom, we have the grip force, the grip force rate, the object's position, the object's velocity and the object's acceleration. Vertical lines are drawn at the time points where various lift events are detected. These lines are solid in plots that contain the measurement on which the detection of the event corresponding to the line was based. From left to right, the vertical lines correspond to: the squeeze onset (2), the lift onset (1), the maximum acceleration, the minimum acceleration and the object height stabilization (3). The magenta vertical line (1) indicates the time point that was set to zero for all measurements. The segment of the measurements highlighted in red (between (2) and (3)) is the segment that is referred to as the lifting curve (see Figure 8). The blue dots illustrate the metrics that summarize the coordination of grip force in this trial (see Figure 9). From left to right, the dots correspond to the peak grip force rate (angled line in grip force plot), the peak grip force and the stable grip force. The grip force measurements that are highlighted in blue to the right of the object height stabilization (3), correspond to the measurement samples of which the mean was defined as the stable grip force.

1) *Lifting phase:* The grip force and position measurements, obtained during the lifting phase of the typical trial (Figure 6), are, along with several of their derivatives, presented in Figure 7. In this figure, the detected segment of the measurements in which the object is squeezed and lifted to a stable position, which will be referred to as lifting curves for the remainder of this report, are visualized.

To extract the lifting curves from the measurements obtained during the lifting phase, the lift onset is detected first. This

event resembles the instant at which the object is lifted and, consequently, breaks contact with its support. It is detected by, first, extracting the time point at which the object acceleration is at its maximum during the lifting phase, and subsequently finding the moment before this time point, at which the object velocity is equal to zero for the last time. Next, the grip onset is detected. This event resembles the instant at which the object is squeezed in order to lift the object, and is marked by the grip force rate being equal or smaller than zero for the last time before the lift onset. To improve the robustness of the grip force onset detection, instants at which the participant is already squeezing the object (i.e. when the grip force is greater than 10% of the maximum grip force exerted during the lifting phase) are not considered for detecting the grip force onset. Last, the lift completion is detected. This event resembles the instant at which the position of the object stabilizes after being lifted and its detection holds similarities to the detection of the lift onset. It is correlated to the instant at which the object velocity is equal or smaller than zero for the first time after the object acceleration hit its minimum. In two cases where the object velocity did not fall below zero before the end of the lifting phase, this event was correlated to the first instant, after the object acceleration minimum, at which the velocity was smaller than the 25th percentile of all the object velocity samples obtained in this time span.

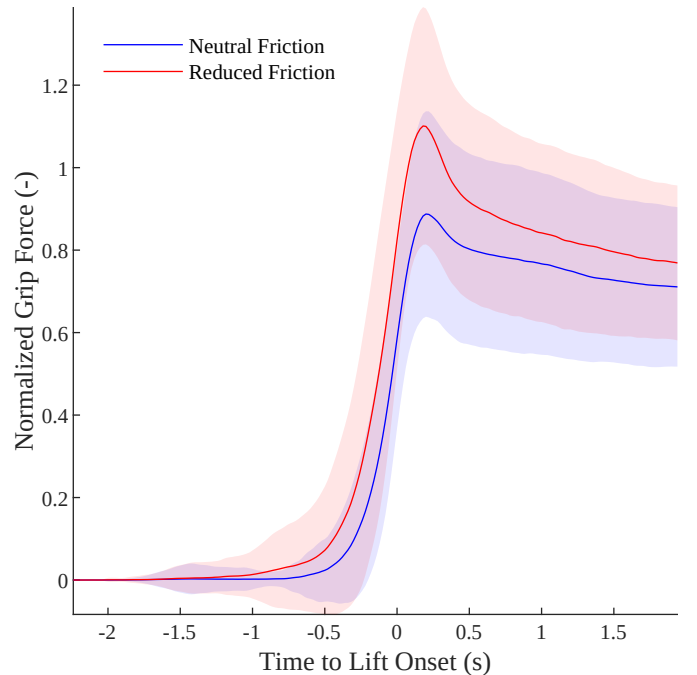


Fig. 8. **Lifting curves (N=20)** In this figure, the solid lines correspond to the lifting curves averaged as function of the initial friction condition. The shades illustrate the standard deviation of the lifting curves as function of the initial friction condition. The curves are normalized using the maximum value of the averaged lifting curve for each participant. The process in which the lifting curves are extracted is visualized in Figure 7.

To yield a more robust lifting curve detection, both the grip force and position data were low pass filtered before attempting to detect the various lifting events. This filtering was done with a 2nd-order zero-phase digital Butterworth filter with a cut-off frequency of 2.7 Hz and prior to the

derivation of the derivatives of both measurements. Filtering out high frequencies largely decreased measurement noise that would otherwise be massively amplified when differentiating the measurements, and consequently would occasionally result in faulty lift event detection. The cut-off frequency was determined by decreasing the frequency in increments of 0.1 Hz, until no faulty lift event detection occurred. However, one faulty lift event detection was eventually conceded (as can be seen for participant 5 in [section C](#)), as the cut-off frequency had to be excessively much lower to correctly detect this event as well.

In order to decrease temporal variability when lifting curves are combined, the curves were synchronised at the lifting onset, and, subsequently, extended to fit the time vector associated with the entire curves collection. This extension is achieved by reincluding measurements that were cropped out earlier in the process of obtaining the individual lifting curves. In some cases, the start of a measurement was too short to allow for a sufficient extension of its corresponding lifting curve and is, therefore, zero padded.

III. RESULTS

A. Lifting phase

1) *Curves*: In [Figure 8](#), the unfiltered lifting curves produced by every participants in this study (see supplementary results in [section C](#)) are combined as explained in [II-E1](#), normalized per participant and finally presented averaged according to the initial frictional condition. As a result, this figure allows a visual assessment of whether people, in general, coordinate their grip force differently for a neutral initial

friction condition, as compared to a, by ultrasonic lubrication, reduced initial frictional condition.

The lifting curves are normalized per participant, using the maximum grip force value of the mean lifting curve for that participant. The goal of this normalization process is to effectively reduce between-participant lifting curve variance, in an attempt to isolate the within-participant lifting curve variance. This within-participant variability is relevant for placing the difference between the mean lifting curves, as function of the initial frictional condition, into context. Indeed, judging from the within-participant variability and the difference between the mean lifting curves, the hypothesized effect of the initial frictional condition on the coordination of grip force seems to be there. The next section will examine whether this effect can be significantly ascribed to the initial frictional condition, by statically analysing metrics that summarize the coordination of grip force during an object lift.

2) *Metrics*: [Figure 9](#) gives an overview of all the metrics that were extracted from measurements in this study, and summarizes how grip force was controlled when lifting an object with a neutral or reduced frictional condition. The peak grip force and peak grip force rate, for each lifting phase, are extracted from the filtered lifting curves as visualized in [Figure 7](#). This figure also presents the selected grip force measurement samples that were averaged to obtain the stable grip force metric. These grip force measurement samples were selected when the absolute value of its rate belonged to the lowest half of the values obtained after lift completion. The lifting metrics were extracted from the filtered lifting phase measurements in order to boost the impact of long term predictive grip force coordination, and to reduce the impact of

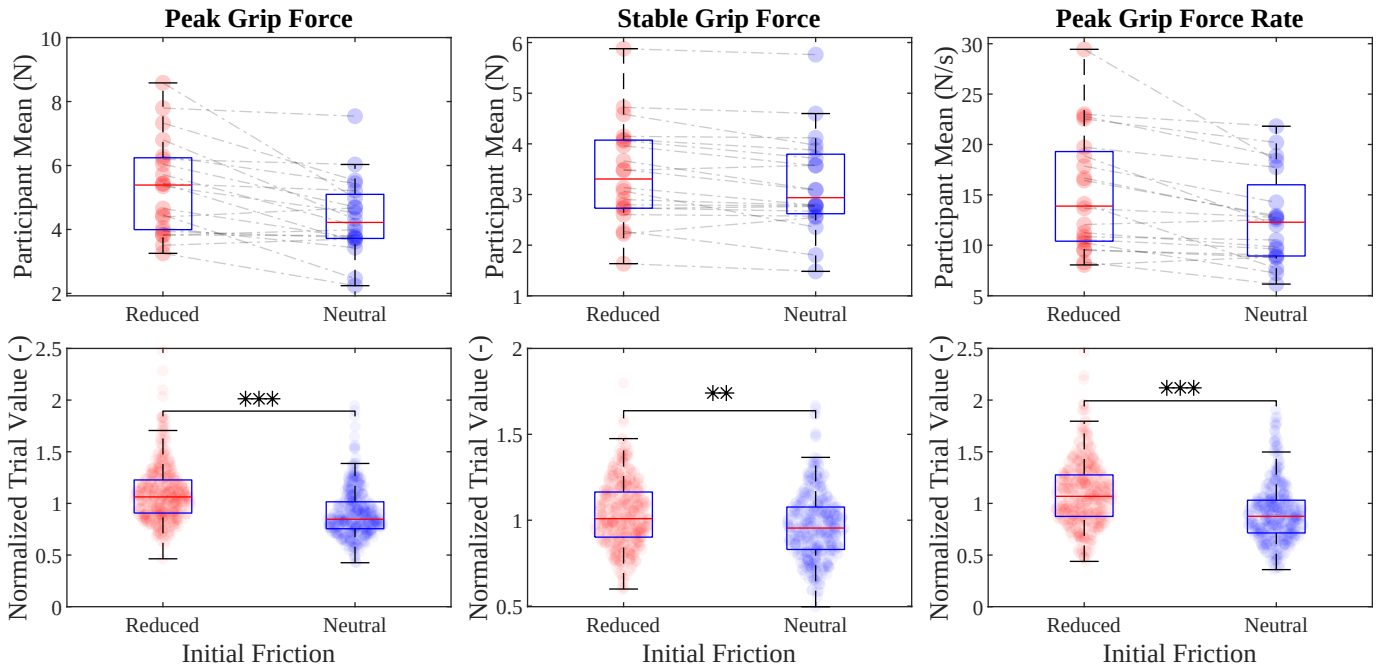


Fig. 9. **Lift metrics (N=20)** In this figure, the metrics that summarize the coordination of grip force during lifting are presented. The top plots contain the mean of all corresponding metric values as function of the initial friction condition and participant. The bottom plots contain all corresponding normalized metric values. These values are normalized using the participant mean of all corresponding metric values. The stars in the bottom subplots indicate that there is a significant difference between the metric values (**: $p < 0.01$, ***: $p < 0.001$). The derivation of the lifting metrics is visualized in [Figure 7](#).

random variability coming from motor noise and occasional high frequency grip coordination corrections.

For each metric, both the paired participant means and all normalized trial values are shown for the neutral and reduced initial friction conditions. The trial values were normalized by the overall mean of the participant that executed a respective trial. As a result, these values provide a compelling insight into the general within-participant grip force coordination variance, and into the average correlation between the coordination of grip force and the initial frictional condition. The top subplots, on the other hand, powerfully illustrate both the between-participant grip force coordination variance in general, and the between-participant variability of the effect the initial frictional condition has on the coordination of grip force.

All three grip force coordination metrics were shown to significantly depend on the initial frictional condition, using a one-way repeated measures analysis of variance ($ANOVA_{RM}$) with the initial friction conditions (neutral and reduced friction) as factor (peak grip force: $F_{1,19} = 17.435$, $p < .001$, stable grip force: $F_{1,19} = 13.129$, $p = .0018$ and peak grip force rate: $F_{1,19} = 17.775$, $p < .001$). The next section will show whether the coordination of grip force also significantly adapts to preceding friction perturbation.

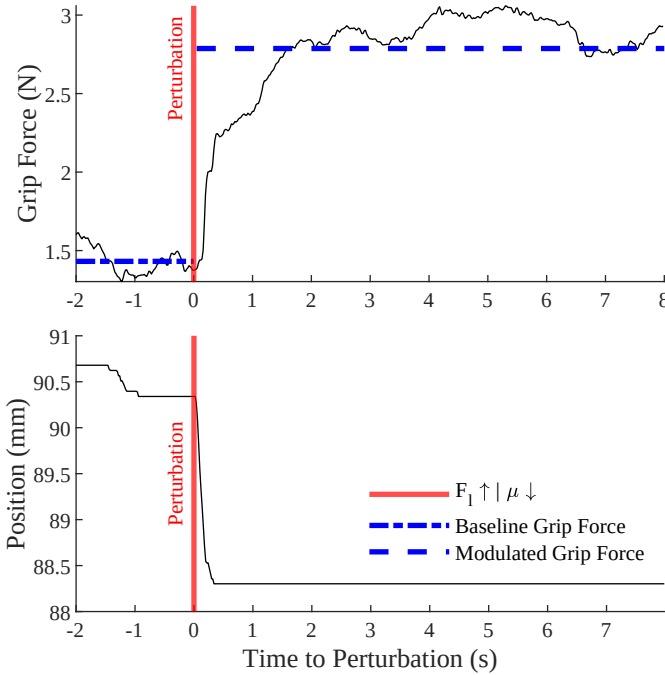


Fig. 10. This figure presents the measurements that are obtained during the holding phase of the sample trial (Figure 6). The perturbation applied during this phase was a mix of a load force increase and a friction decrease. The two horizontal blue lines illustrate the baseline (dash-dotted) and modulated (dashed) grip force values. The baseline value was computed by taking the mean of the grip force applied after the beginning of the holding phase and before perturbation. The modulated value was derived by taking the mean of the grip applied between 100 ms after the perturbation and the end of the holding phase. The ratio between the modulated and the baseline grip force values defined the relative grip force change metric. This metric summarizes the distinct change in grip force that follows the perturbation. From this grip force measurement, a holding curve was derived and combined with other holding curves in Figure 11.

B. Holding phase

1) *Curves*: Figure 10 provides a better view of the measurements obtained during the holding phase of the typical trial presented in Figure 6. The grip force change, relative to the baseline grip force, was derived in order to combine these curves:

$$\Delta F_n(t) = \frac{F_n(t)}{\text{mean}(F_n(t < T_{\text{perturbation}}))} - 1 \quad (1)$$

The resulting holding curves were averaged as function of the perturbation condition, and subsequently visualized in Figure 11. For each individual participant, the holding curves, both raw and averaged as function of the perturbation condition, can be found in the participant results appendix (section C).

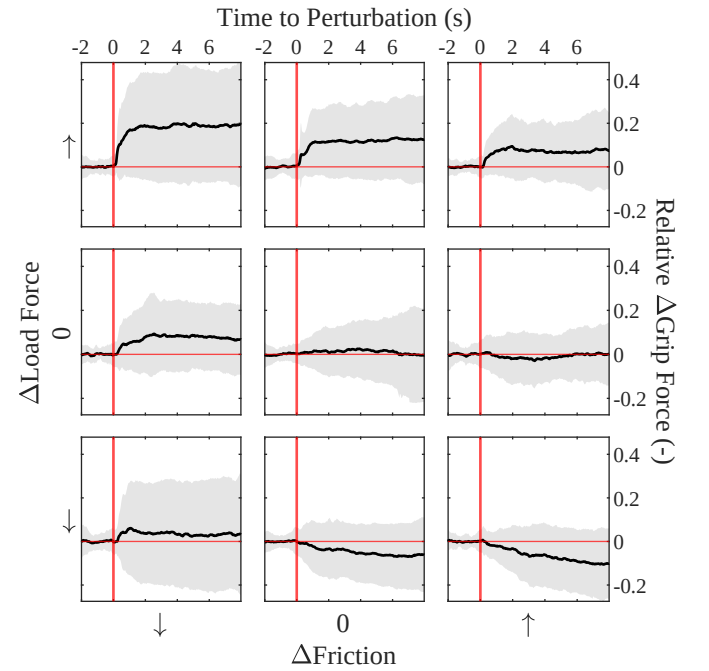


Fig. 11. **Holding curves (N=20)** In this figure, each plot presents the mean (solid line) and the standard deviation (shade) of the holding curves that correspond to the perturbation condition of the plot. The load force and friction changes corresponding to each perturbation condition are presented on the left and bottom respectively. In each plot, two red constant zero lines are drawn. The vertical line indicates the time at which a perturbation was applied, whereas the horizontal line is intended to ease the perception of a relative grip force change as function of time. The derivation of a single holding curves is visualized in Figure 10.

2) *Metrics*: For a single trial, the magnitude of the relative grip force response elicited by the perturbation condition, is expressed in a metric that is determined by dividing the difference between the modulated and baseline grip force, by the baseline grip force:

$$\Delta F_n = \frac{\text{mean}(F_n(t > T_{\text{perturbation}} + 0.1s))}{\text{mean}(F_n(t < T_{\text{perturbation}}))} - 1 \quad (2)$$

The modulated grip force, derived for the typical trial, is illustrated in Figure 10.

The modulated grip force is derived by taking the mean of the grip force that is applied between 100 ms after the

perturbation and the end of the holding phase. The reason for starting the derivation of the modulated grip force 100 ms after the perturbation, instead of right after the perturbation, is that the minimal latency, at which potential grip reflexes to perturbations are induced, is commonly known to be barely lower than 100 ms [18], [19]. Including these grip force measurements might, therefore, only introduce passive grip force variability (induced by e.g. non-linearities of the fingertip) into the metric of the actively controlled grip force response.

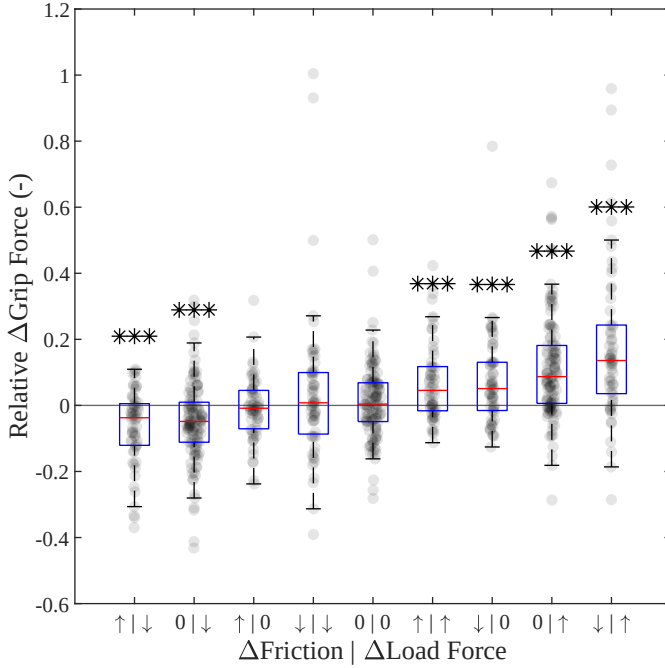


Fig. 12. **Relative grip force change metric (N=20)** In this figure, the metric values that summarize the adaptation of grip force in response to the various perturbation condition are presented for all trials. Stars indicate that the modulated grip force for the corresponding perturbation condition are significantly different from the baseline grip force (***: $p < 0.001$). The derivation of the relative grip force change metric is visualized in Figure 10.

In Figure 12, the individual relative grip force changes elicited in all trials, are presented as function of the perturbation condition. The significance of these changes were tested using a paired t-test. Significant unequivocal differences between the modulated grip force and the baseline grip force were not observed for the friction increase condition ($t(59) = 1.36$, $p = .18$), the friction and load force decrease condition ($t(59) = -1.06$, $p = .29$) and the control condition ($t(119) = -0.964$, $p = .34$)).

However, highly significant differences between the modulated grip force and the baseline grip force were detected for both load force perturbations (decrease: $t(119) = 4.93$, $p < .001$, increase: $t(119) = -7.64$, $p < .001$), for a friction decrease ($t(59) = -3.96$, $p < .001$), for a friction decrease in combination with a load force increase ($t(59) = -5.92$, $p < .001$) and for a friction increase in combination with a load force decrease ($t(59) = 4.24$, $p < .001$) and increase ($t(59) = -4.54$, $p < .001$).

IV. CONCLUSION AND DISCUSSION

We measured the grip adaptations in response to various perturbations of a stable precision grip on an object. These perturbations included changes of the friction at the contacts between the object and the fingers engaged in the precision grip. We have observed how a decrease of friction elicited grip adaptations likely intended to restore the safety margin over the increased minimum required grip force. An increase of friction, on the other hand, was not observed to precede unequivocal and significant adaptations of grip force. The asymmetry of these adaptations might not seem remarkable at first sight, considering that the failure to restore an earlier maintained safety margin yields far less potential negative consequences when this failure follows an increase of the safety margin, as opposed to a decrease.

However, the current study and previous studies have demonstrated that other perturbations of the maintained safety margin did always precede grip force adaptations, regardless of the direction of the safety margin change. Indeed, humans adapt their grip force in response to any change of the load force when lifting [5], [8] and statically holding an object [11], [12], [14]. Likewise, humans adapt their grip force in response to both positive and negative changes of the initial friction condition when lifting an object [5]–[8].

So why did participants in the current study not adapt their grip force in response to an increase of the friction between a statically held object and the fingers used to hold it? The inconsistency of grip adaptations can be compared to a similar inconsistency in the perception of friction that was demonstrated by a perception study [20]. Whereas participants were able to perceive ultrasonic friction decreases in this study, they failed to perceive ultrasonic friction increases. These inconsistencies in action and perception can likely both be attributed to hypothesized limitations of our sense of friction.

Currently, friction is believed to be exclusively sensed through its effect on the tangential dynamics in spatio-temporal skin deformation patterns that are encoded in our tactile feedback [16], [20]–[28]. These fingertip deformation patterns emerge when shear strain energy is passively locked by friction and pressure at a surface-fingertip contact. This locked shear strain energy develops when the skin of a fingertip, that is pressed on a surface, wants to expand to retain its initial surface area [21], or simply when a load force on an object is compensated at the fingertip-objects contacts. As soon as the shear strain energy locally saturates the combination of friction and pressure, local slips will occur and a fingertip deformation pattern shaped by the current friction emerges.

This deformation process can be induced by a decrease of friction. The sensation of this process is hypothesized to precede the observed adaptations of the grip force coordination that occur when participants lift objects with unexpected friction conditions [5], [6], [21]. An increase of friction, in contrast, cannot directly reverse this process as visualized in Figure 13. For this reason, and since there are no other known mechanisms with which we could sense friction, humans are likely unable to directly sense increases of friction.

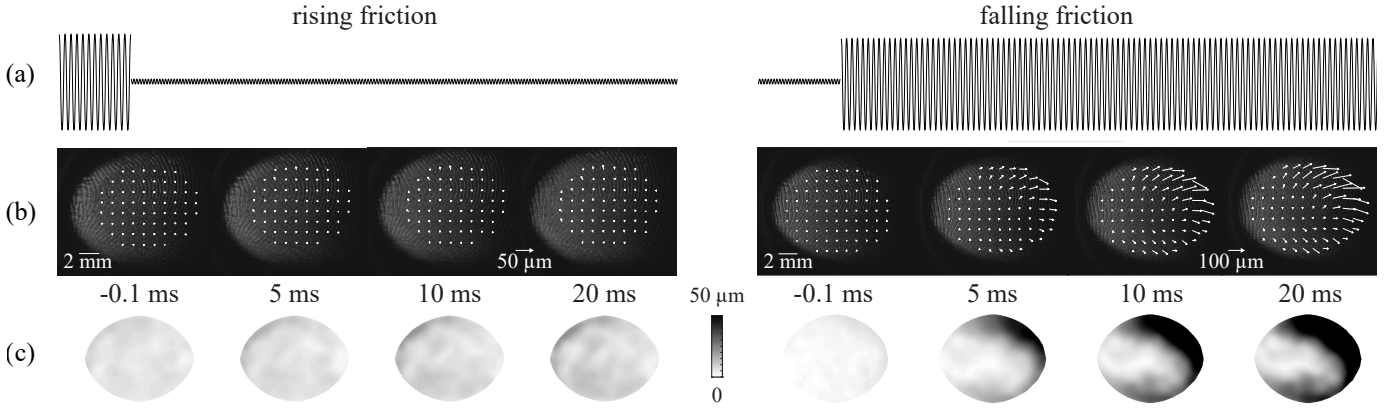


Fig. 13. Tangential deformation patterns for when friction is ultrasonically increased (left) and friction is ultrasonically decreased (right). The resultant force at this fingertip-surface contact acts normal to the contact. (a) Ultrasonic friction modulation driving signal amplitude. This amplitude negatively correlates with friction. (b) Images and deformation field of the skin at selected instants: -0.1 , 5 , 10 and 20 ms relatively to the friction change. (c) Norm of the displacement vector. Adapted from [20].

A. Sensing and adapting to friction increases

When friction is increased, higher increases of shear strain energy or higher decreases of pressure are required to induce new local slips. Therefore, I hypothesize that humans are able to indirectly sense an increase of friction through the absence of fingertip deformation patterns that normally follow an increase of shear strain energy or a decrease of pressure.

Such absence can for example explain the adaptation of the grip force coordination to an increased initial friction condition when lifting objects. Before lifting an object, a prediction on the fingertip deformation patterns that will be sensed as a result of the gradual increase of shear strain energy experienced during lifting, can be predicted based on the initially expected friction. A too low prediction of the friction is, therefore, likely to result in an error between the expected and sensed deformation patterns. This error can result in a sensation of the friction increase, and subsequently elicit the observed adaptations of the grip force coordination to an increased initial friction condition.

Similarly, I do expect that humans could eventually sense the friction increases that I presented participants in this study with. Pressure decreases, induced by sporadic or even controlled grip force decreases, can precede the absence of fingertip deformation patterns that are expected due to a too low estimate of the friction. Here too, this error between expected and sensed deformation patterns could result in a sensation of a friction increase, and a subsequent adaptation of the grip force to the updated friction estimate. Longer post perturbation measurements, random grip force variance decreases and stronger friction increases can help to reveal these hypothesized grip adaptations in future studies.

B. Framework for predicting grip adaptations

An accurate sense of the safety margin is critical for the ability to control the actual safety margin. However, the sensed safety margin is never expected to precisely reflect the actual safety margin, due to limited sensory cues which can be integrated to estimate the actual safety margin. The availability

of sensory cues varies depending on the perturbation. Where both load force increases and decreases can be sensed through many sensory cues, the pool of sensory cues which can be used to sense friction, is hypothesized to be very limited and solely direction dependent. I expect this availability to influence the coefficient of the relation between an actual safety margin change, and the grip force adaptation it precedes. This influence is clearly demonstrated by experiments in which participants had to lift objects with varying surface textures while their sense of touch was fully impaired by means of cutaneous anaesthesia. As a result of this impairment, the coordination of grip force completely ceased to adapt to the initial friction condition [5], [8].

C. Friction perturbations

We have observed that, when lifting an object, the relation between the coordination of grip force and the initial friction condition can be reproduced by varying this condition using ultrasonic lubrication. As a result, we conclude that inducing partial squeeze films, using ultrasonic lubrication, is a viable method for perturbing the friction in a precision grip experiment.

The main benefit of this new method is that friction can be perturbed during any stage of a precision grip experiment, as opposed to the existing methods, with which the friction could only be changed before it was gripped by e.g. changing the topography of the object's surfaces or their treatment [5]–[8]. The main disadvantage of the new method is that the magnitude of practical friction perturbations is currently still limited by the unbearable heat that can be produced by higher vibration amplitudes. The exact mechanics that underlie this production of heat remain elusive. As the heat that was produced for a constant vibration amplitude varied highly from time to time and per person, more factors, besides vibration amplitude, are expected to influence the heat that is produced. Researching what these factors are, and how they can be controlled, can prove to be decisive for improving the strength of the ultrasonic friction perturbations that can be applied without occasionally producing unbearable heat.

Where sensory cues on the texture or treatment of the surface often provides indirect cues on the changes of friction induced using traditional methods of perturbing friction, auditory cues and sensed changes of temperature at the object-interfaces can still provide salient and indirect cues on changes of friction induced using the new method. In the current study, the subsonic noise produced by the friction modulation plates was successfully cancelled and drown out by headphones and audio of the nature documentary. In future studies, temperature change cues could be limited by using heating elements and heat sinks to control a constant temperature at the fingertip-object contacts.

The magnitude of the friction perturbations applied in the current experiment varied heavily and could not be confidently monitored. Obtaining an accurate estimate of the perturbation magnitudes will allow robust computations of the change of the safety margin that is maintained throughout a trial. An analysis of these friction changes can provide improved insights into how the safety margin is controlled following friction or mixed perturbations. Furthermore, improving the control over the friction perturbation magnitudes can help to balance the impact that friction and load force perturbations have on the safety margin in future studies.

D. *Sweaty fingers*

Following friction decreases, many participants in this study obtained the perception of their fingers becoming extremely sweaty. This perception even initially made some of the participants insecure about their execution of the experimental protocol. The degree of this initial insecurity is likely related to the steepness of the trial by trial adaptation discussed in [section B](#).

While I did not test whether friction decreases did actually increase perspiration, I hypothesize that this perception, in fact, did not fully reflect reality, and that this perception was heavily influenced by top-down processes in the nervous system shaped by the participant's expectations and prior knowledge. In simpler words: due to a lack of other logical explanations, the brain altered the perception of perspiration in order to explain the sudden decreases of friction.

This perception might cease to arise during object lifts, if the impression of a potential object surfaces change is given when the object is not gripped. In this case, participants could attribute any changes of friction to a change of object surfaces. All with all, I do expect participants to stop attributing friction perturbations to perspiration as they become familiar with the perturbations.

E. *General recommendations for precision grip studies*

In this study, two unconventional methods were employed to promote efficient and natural grip force control. The first method, which is the auditory feedback on threshold exceeding grip forces intended to promote the efficient grip force control, did not yield satisfactory results. I expect that, like participants in many precision grip studies in the past, the participants in this study would have adapted to efficiently control their grip force regardless of the employment of this

method. Therefore, this method was only found to introduce undesirable influences which potentially slightly masked the differences between the grip force coordination as function of the initial friction conditions. Furthermore, it might have made participants reluctant to respond to perturbation conditions. As a result, I do not recommend providing similar feedback in future precision grip studies.

The second method, which is the provision of an optional activity that could be executed while manipulating objects, seemed to boost natural grip force control. In daily life, humans generally do not lift and hold objects while fully focusing on this task. They often manipulate objects while executing other tasks, like watching a nature documentary as participants did in this study. Therefore, this optional extra activity helped participants feel at ease during the experiment and presumably prevented unnatural attention to what was happening to the object and possible conscious grip control interventions. Finally, it made participating in this experiment much more enjoyable for the participants. Therefore, I wholeheartedly recommend providing similar optional activities and researching their effect in future precision grip studies.

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APPENDIX A NATURE DOCUMENTARY QUIZ

After the experiment, the last 18 participants that were included in the result analysis were unexpectedly invited to voluntarily complete a quiz on the the nature documentary they could watch during the experiment. The goal of this quiz was to quantify the mental capacity participants spend on watching this documentary.

The quiz contained 5 multiple choice questions with each 4 different answer options. The answer options were randomly ordered for every participant. All of the invited participants agreed to complete the quiz. The participants (N=18) answered 3.00 ± 1.03 out of these 5 questions correctly. The list of questions and respective answer options are listed below. The correct answer to each question is indicated in bold.

- 1) What portion of land on our planet is covered by desert?
 - A. 1/3
 - B. 1/4
 - C. 1/5**
 - D. 1/6
- 2) Where do the birds in the beginning of the documentary get their food?
 - A. The dessert
 - B. The sea**
 - C. The forest
 - D. The grasslands
- 3) Out of how many elephants did the elephant herd in the documentary exist?
 - A. 4
 - B. 8**
 - C. 12
 - D. 16
- 4) Which elephant managed to reach the leafy branches of the ana trees?
 - A. A matriarch
 - B. A bull**
 - C. A calf
 - D. None of the above
- 5) Which animal was not featured in the nature documentary?
 - A. Lynx**
 - B. Lion
 - C. Cheetah
 - D. Leopard

APPENDIX B TRIAL BY TRIAL ADAPTATIONS

[t!] [Figure 14](#) provides an intriguing insight into how participants adapted their coordination of grip force, when lifting the object multiple times, and how the difference between the coordination of grip force, as function of the two frictional conditions, developed. For this results analysis, the data obtained during the familiarization phases are included as well, as it contains the initial adaptation. The magnitude of the grip force metrics seems to decrease as function of the trial number. This result could be explained by the increased familiarity with the object, and the increased confidence in the estimates of its properties. Such confidence increase has, indeed, been shown to result in a decrease of the safety margin maintained over the minimum required grip force [3], resulting in lower employed grip forces in general. The adaptation could also be caused by a gradual increase of friction with an increasing number of completed trials, resulting in a decrease of the minimum required grip force. Such friction increase can originate from changing fingertip properties, changing surface properties, or changing grip postures [5], [7], [28]–[32], [32], [33], [33]–[38].

Similar causes could also underlie the seemingly adaptation that results in a decrease of the difference between the grip force metrics, as function of the two frictional conditions. This adaptation could, furthermore, be induced by an anticipated sudden decrease of friction later in the trial, which can influence the magnitude of the maintained safety margin [3]. Such change would only be expected when the initial friction is neutral, resulting in an increased safety margin, as compared to the reduced initial friction condition. As the confidence in an expected friction change grows stronger with an increasing number of completed trials, the difference between the safety margins applied for both initial friction conditions will increase as well, gradually cancelling the existing difference in the minimum required grip force for both conditions. In this case we would primarily expect the difference between the stable grip force metric for both initial friction conditions to decrease, as the perturbations were applied, and in that case probably expected, only after the grip on the object had stabilized. However, the difference between the stable grip force metric for both initial friction conditions seems to actually decrease less, as compared to the difference for the two other metrics.

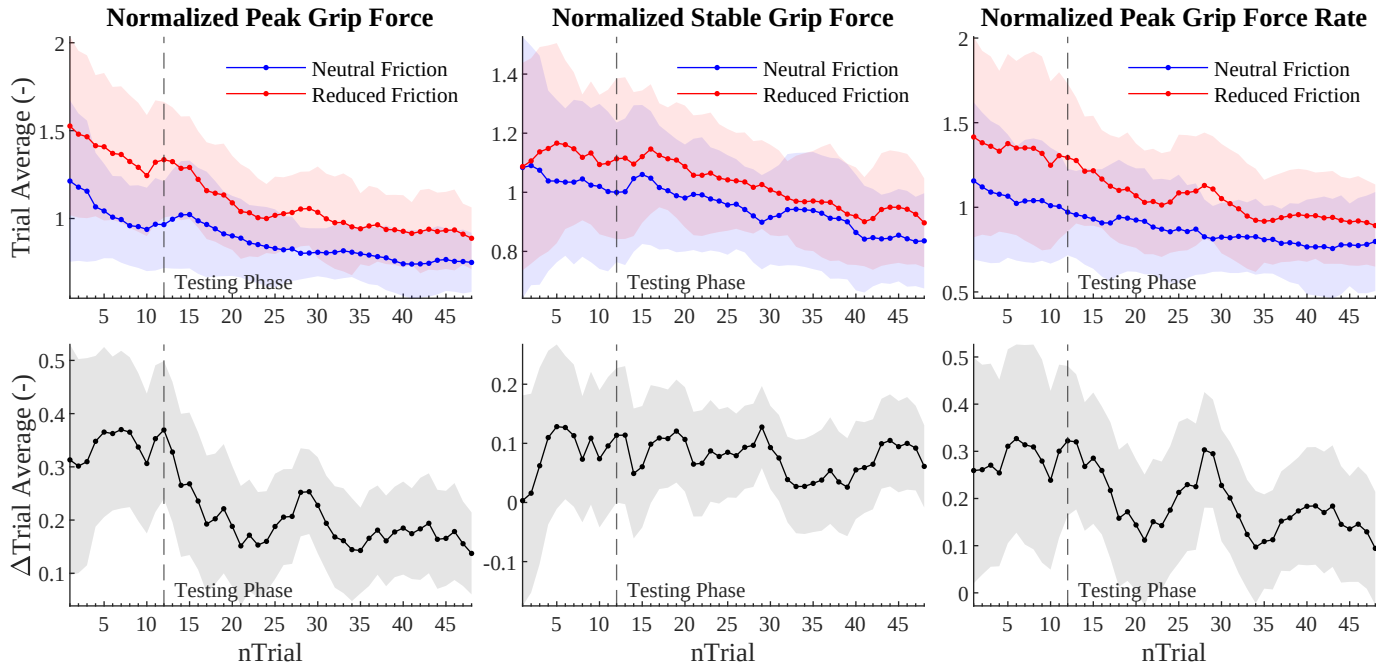
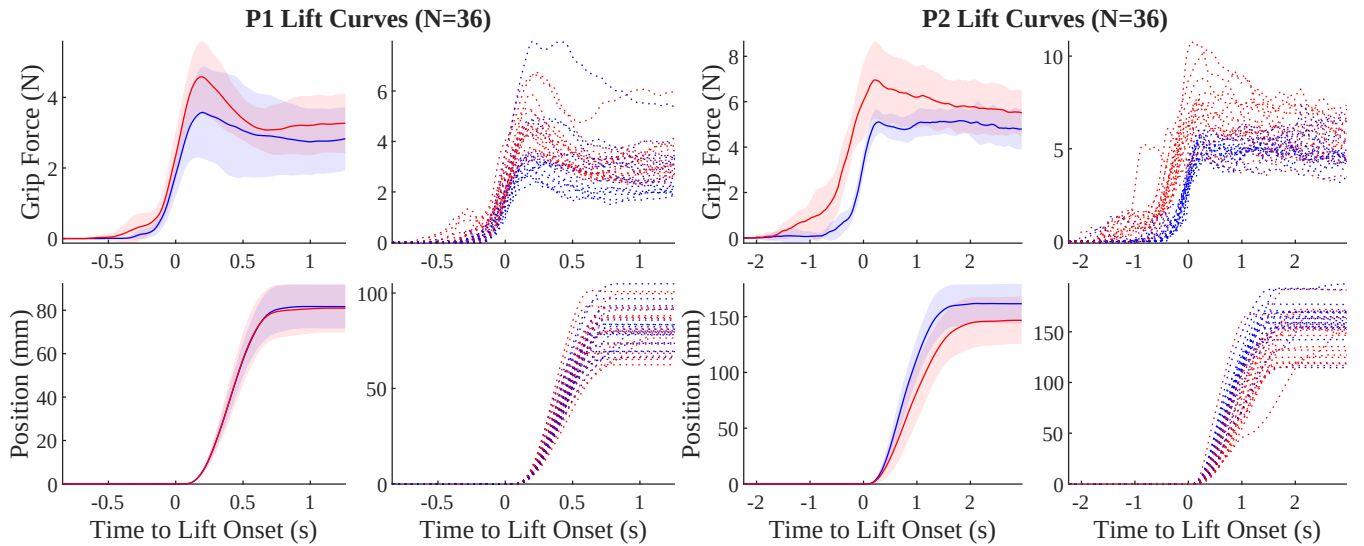
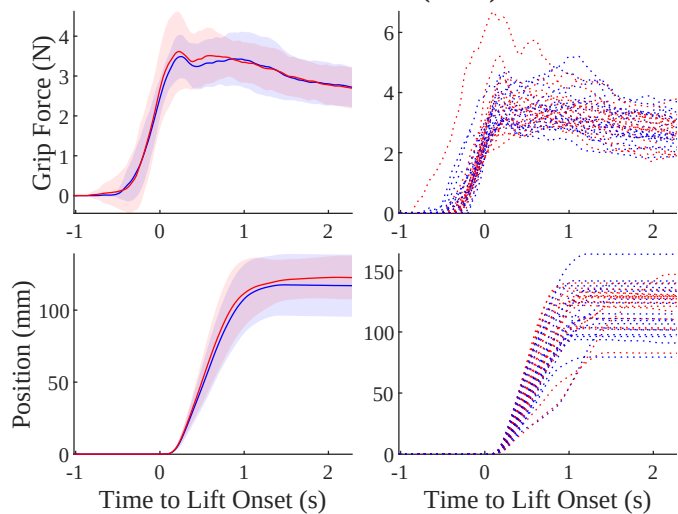
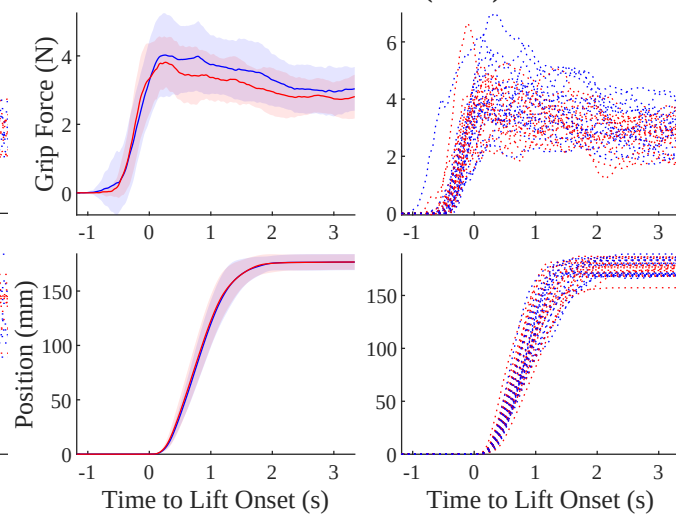
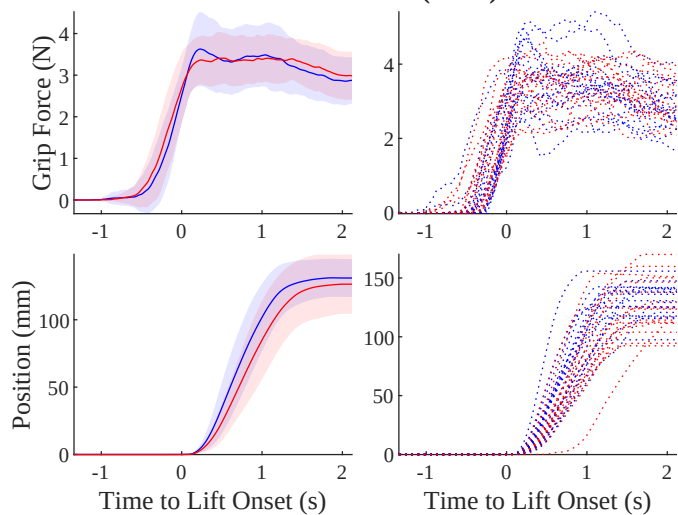
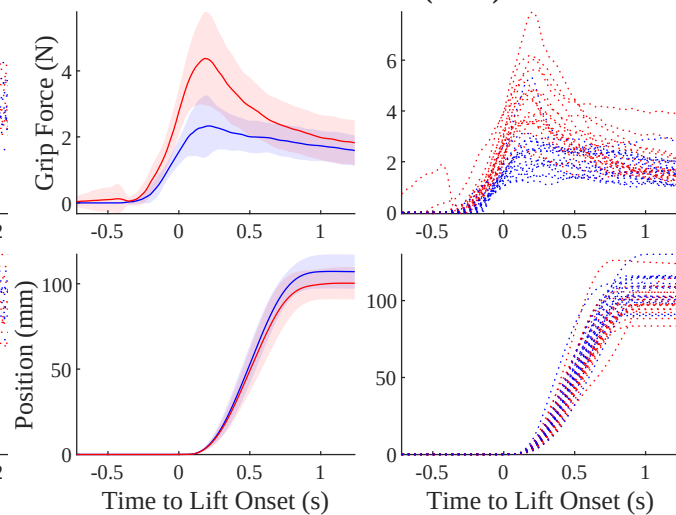
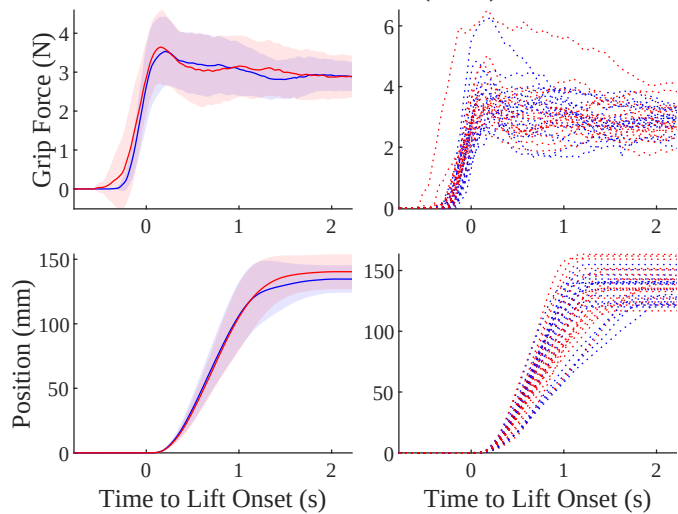
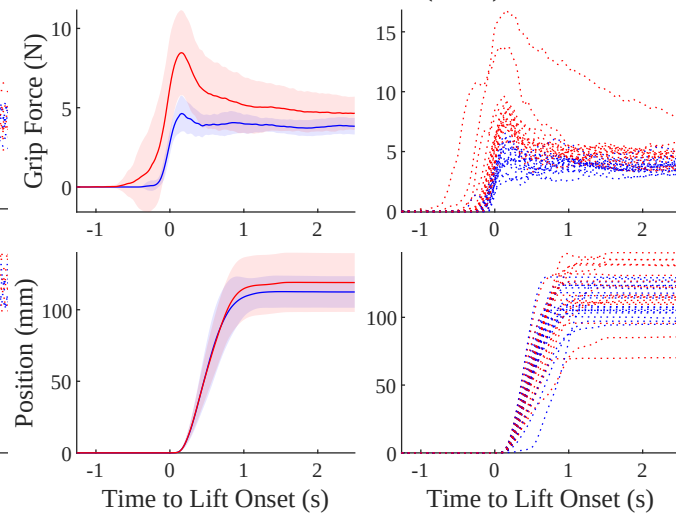
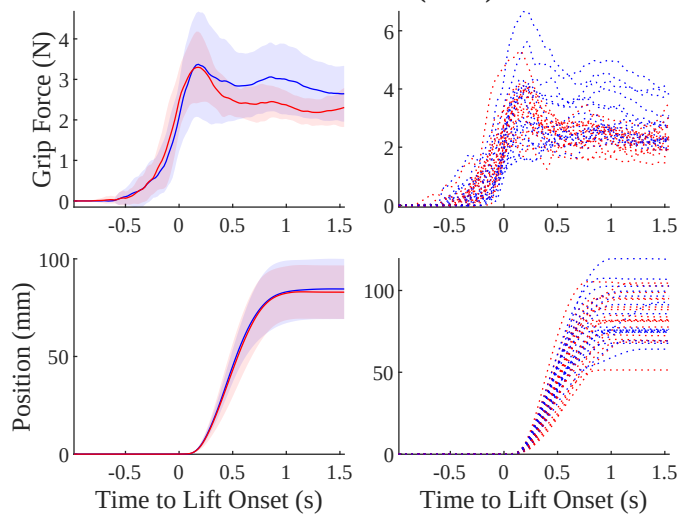
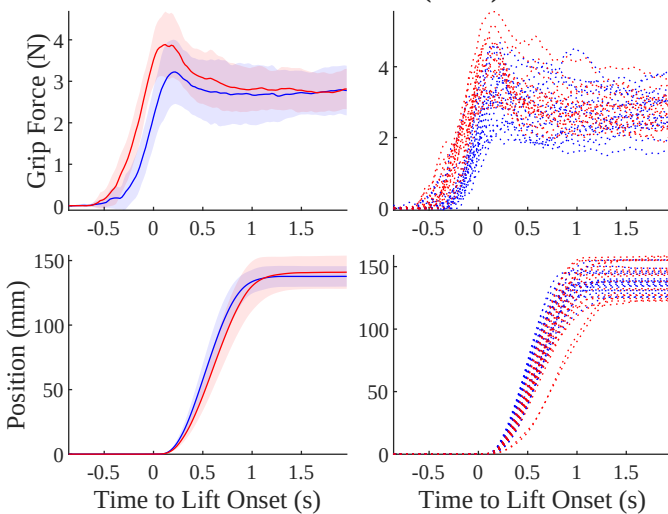
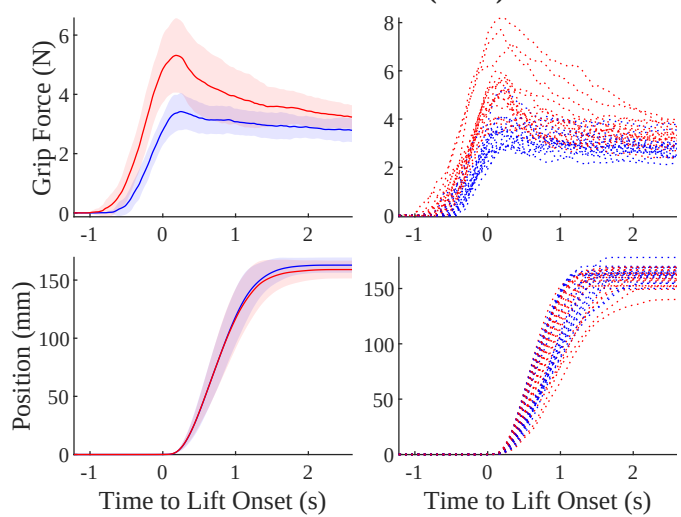
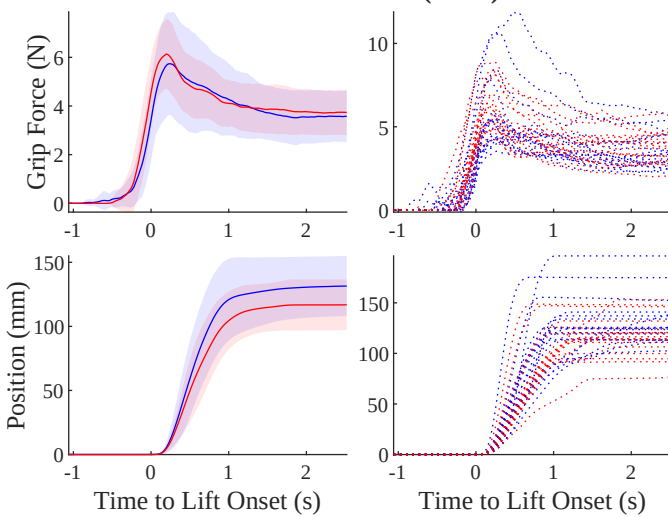
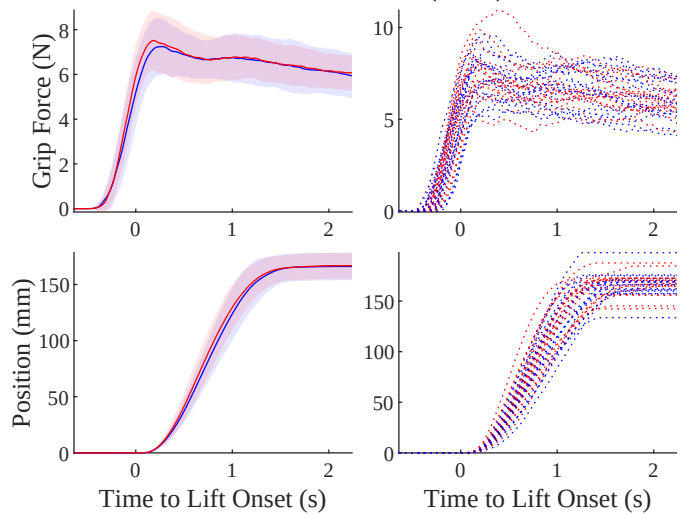
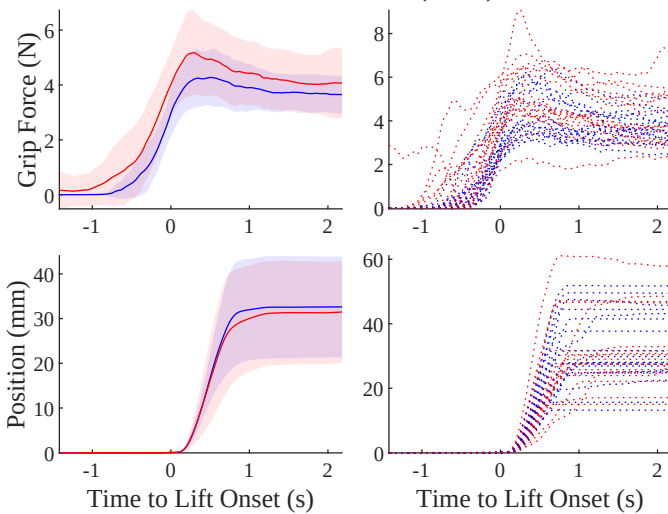


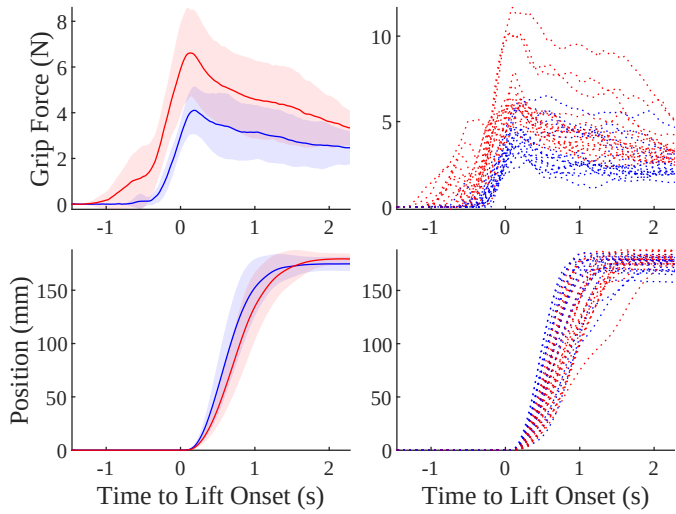
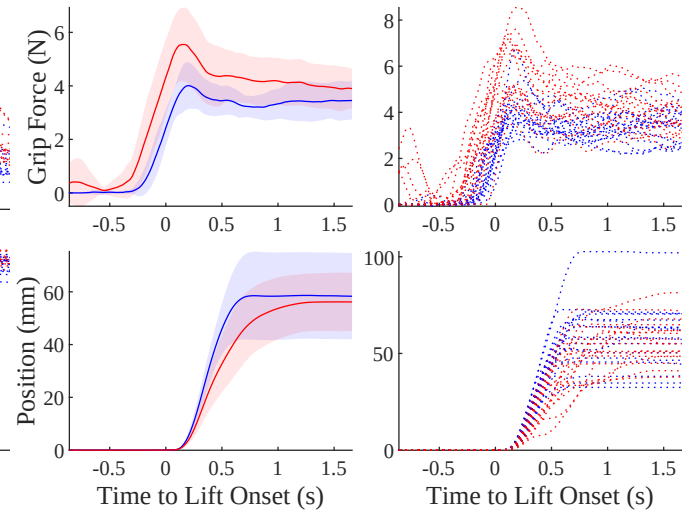
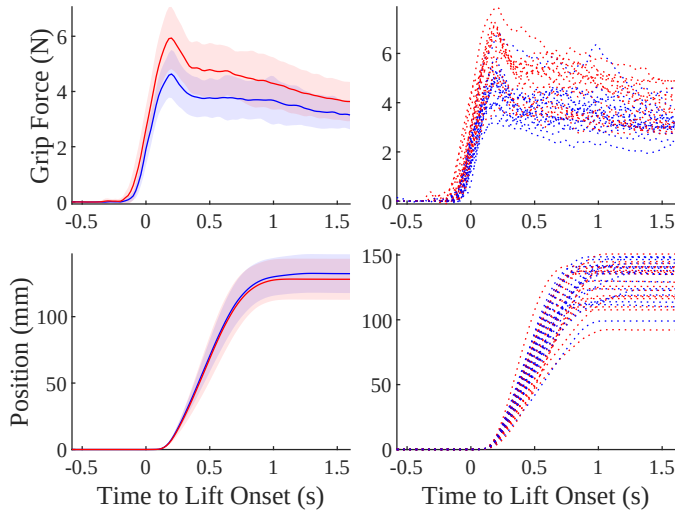
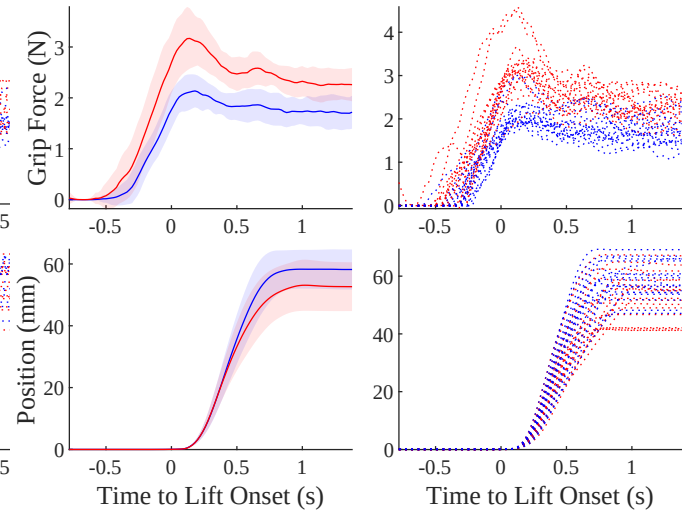
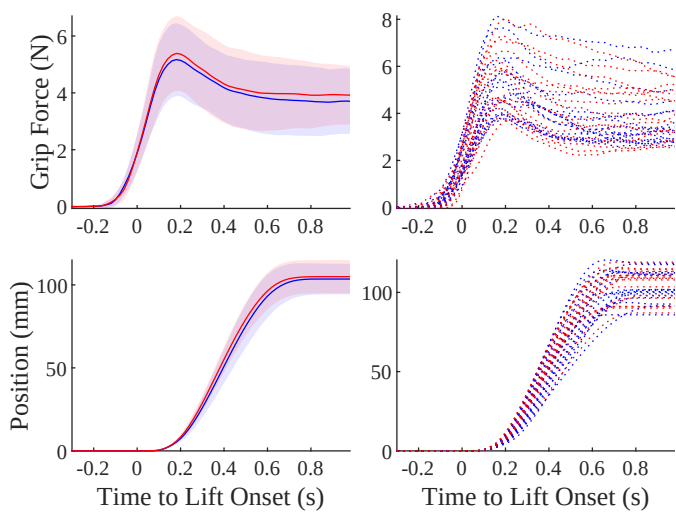
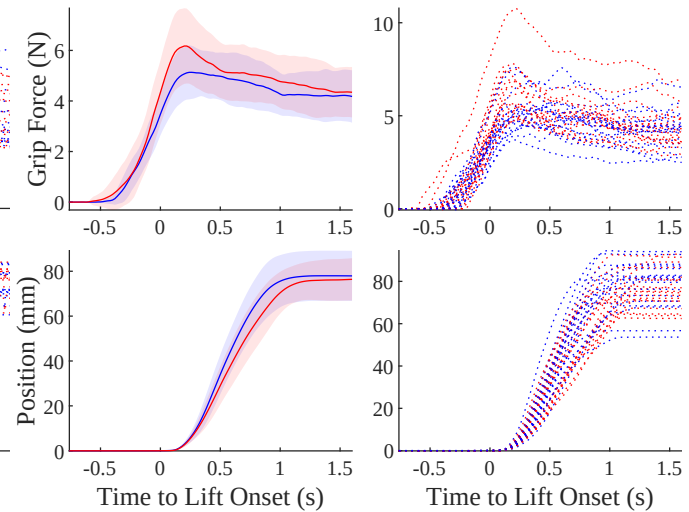
Fig. 14. In this figure, the metrics that summarize the coordination of grip force are presented to show how the coordination of grip force adapted trial by trial. The top plots contain the mean (solid line) and standard deviation (shade) of all corresponding metric values as function of the initial friction condition and trial number. The bottom plots illustrate the trial by trial adaptation of the difference between the mean (solid line) of all corresponding metric values as function of the initial friction condition. The standard deviation corresponding to this mean (shade) is furthermore visualized. In all plots, the transition between the familiarisation and the testing phase is indicated using vertical dashed lines. The derivation of the lifting metrics is visualized in Figure 7.

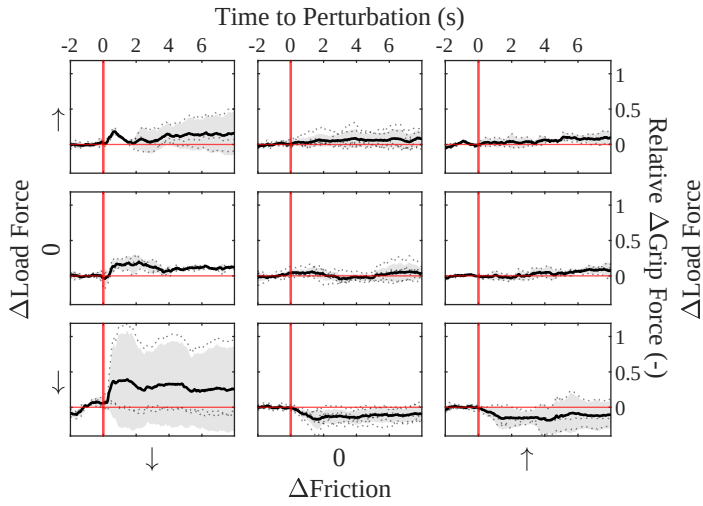
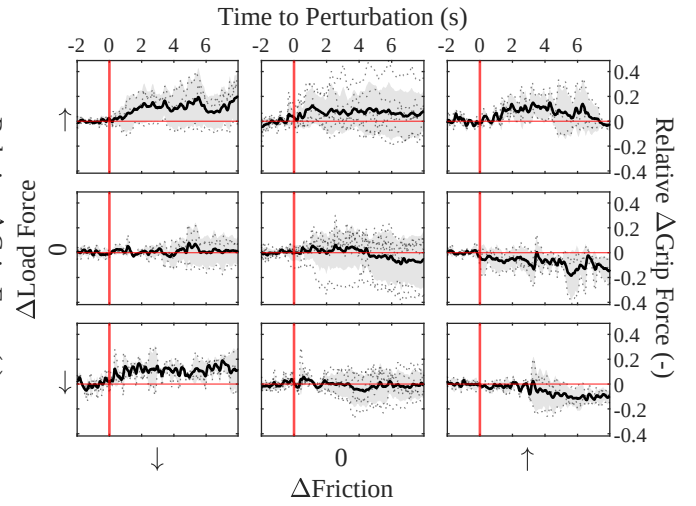
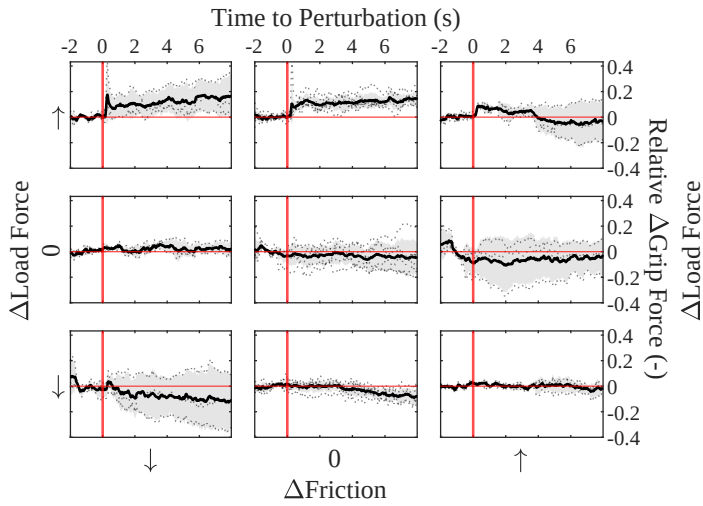
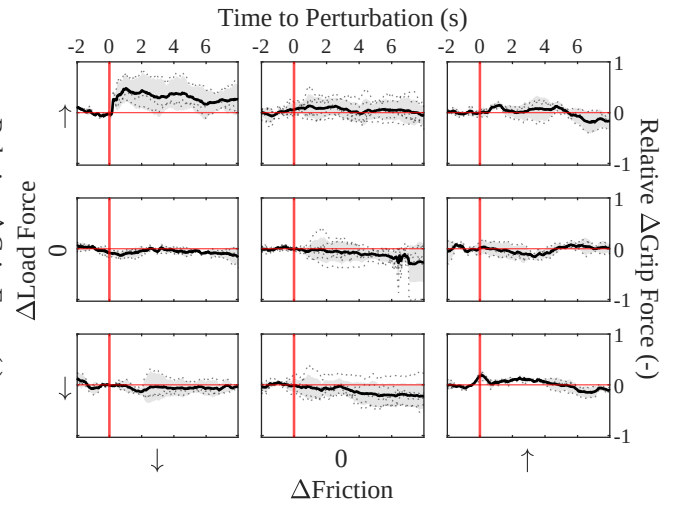
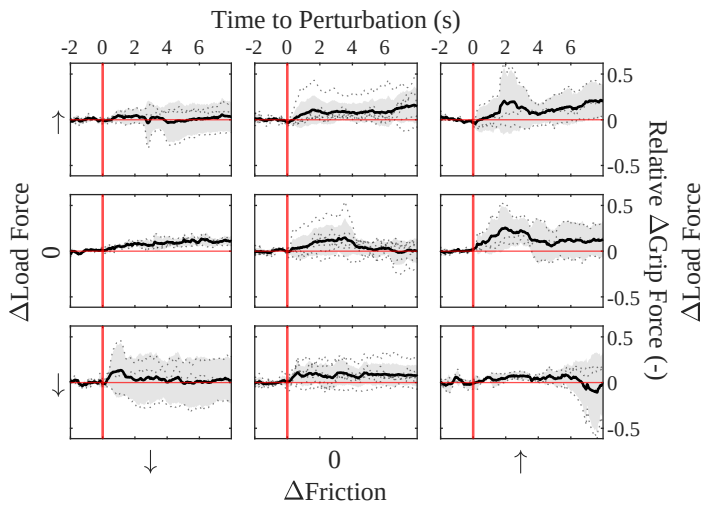
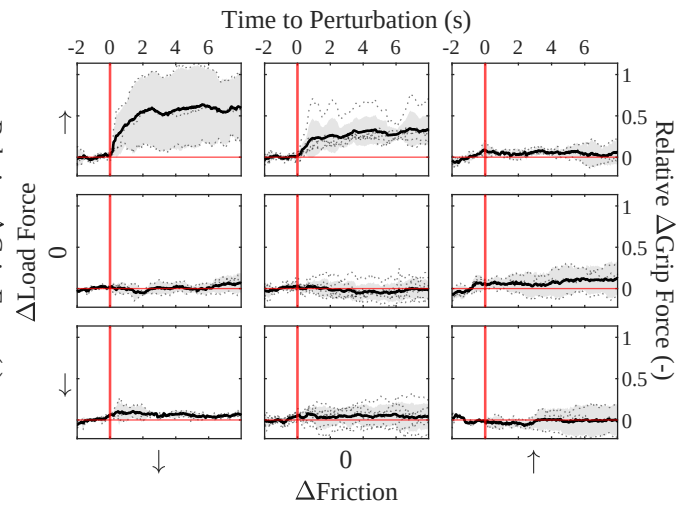
APPENDIX C PARTICIPANT RESULTS

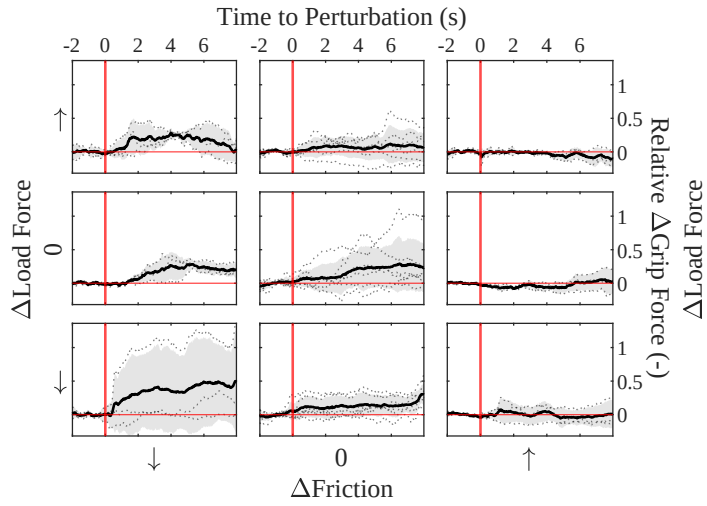
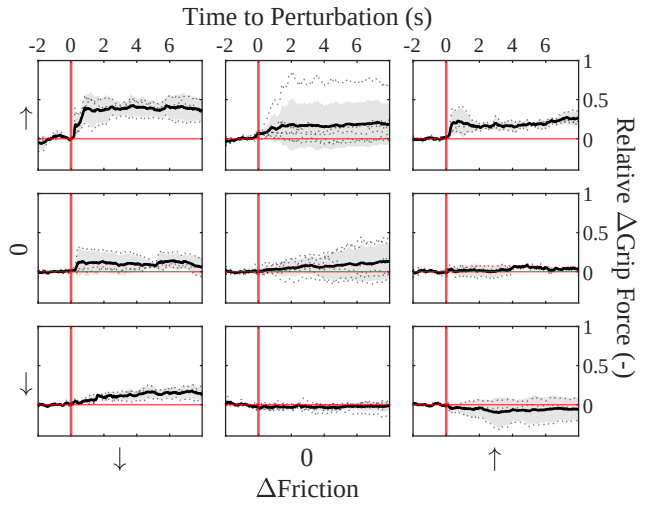
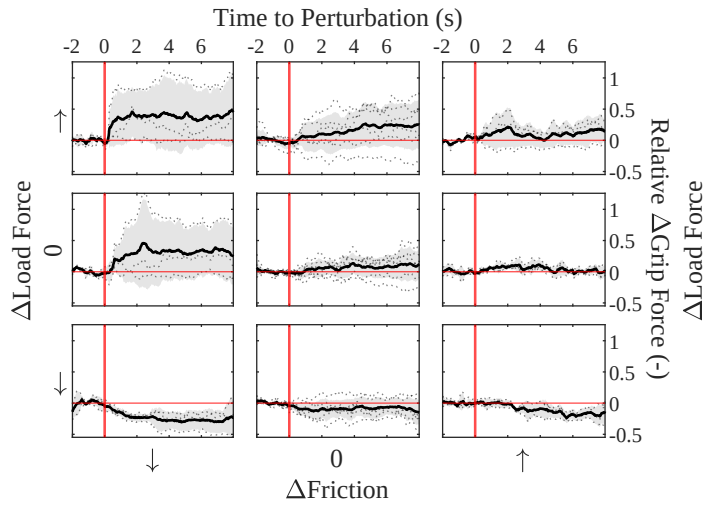
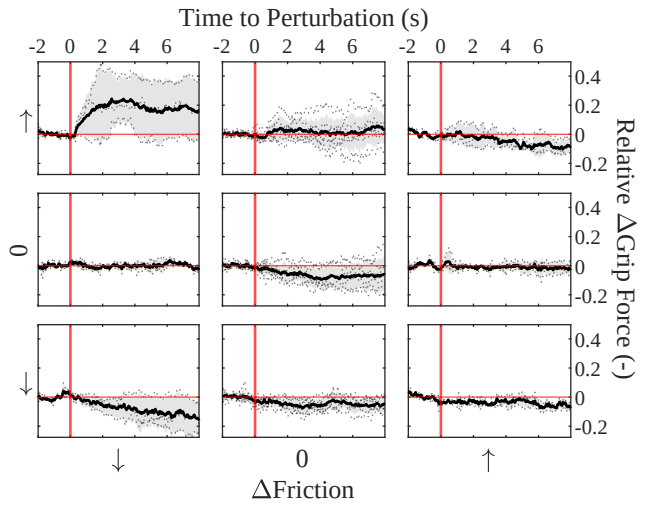
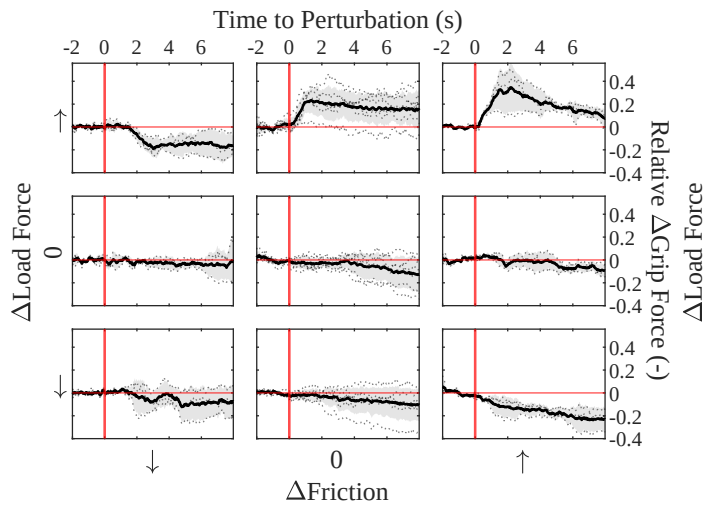
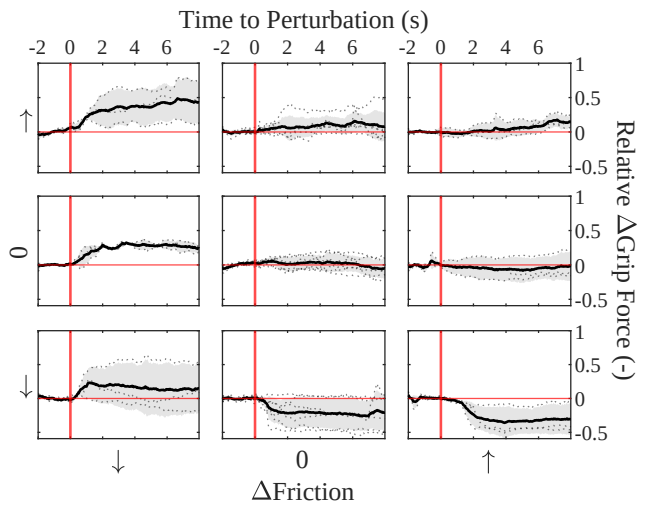


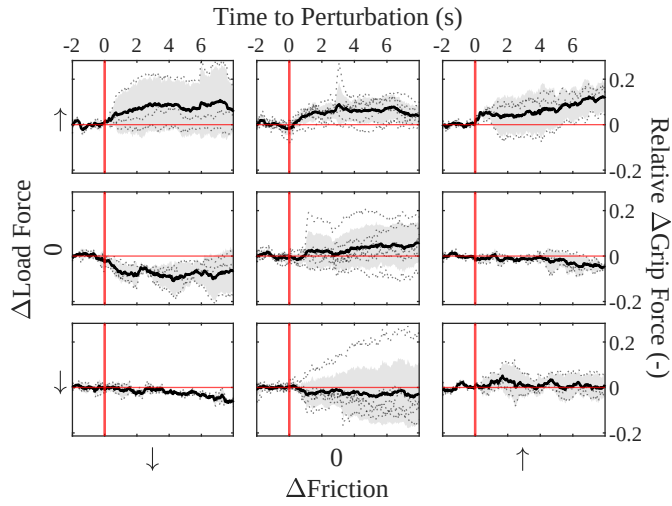
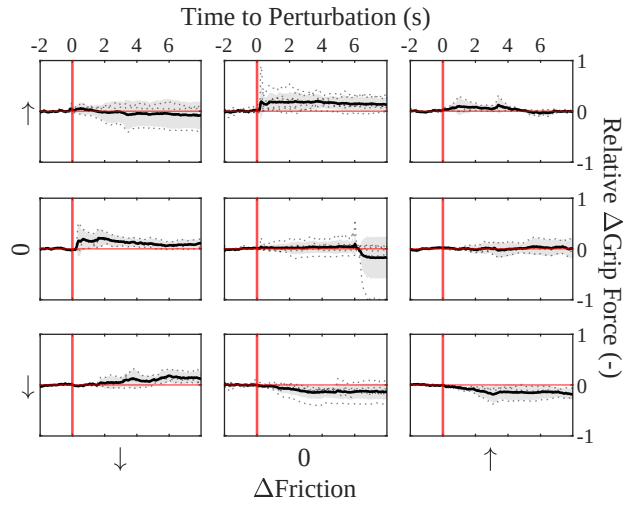
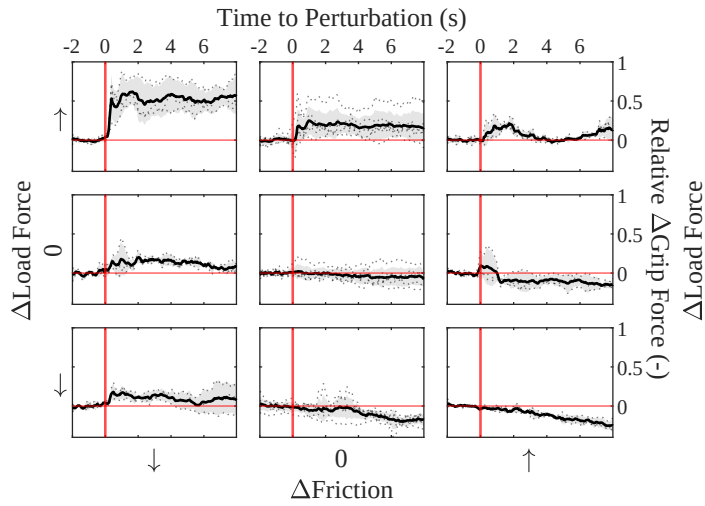
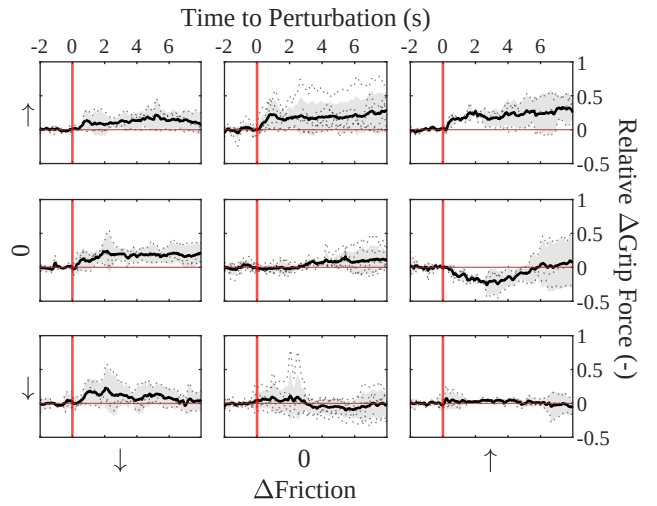
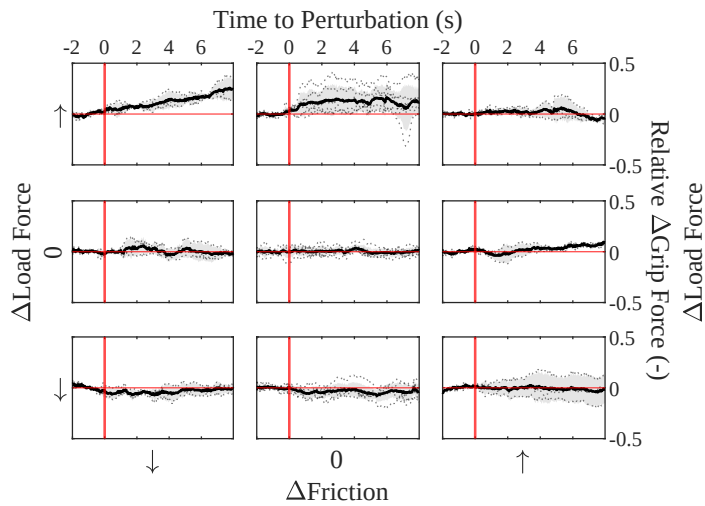
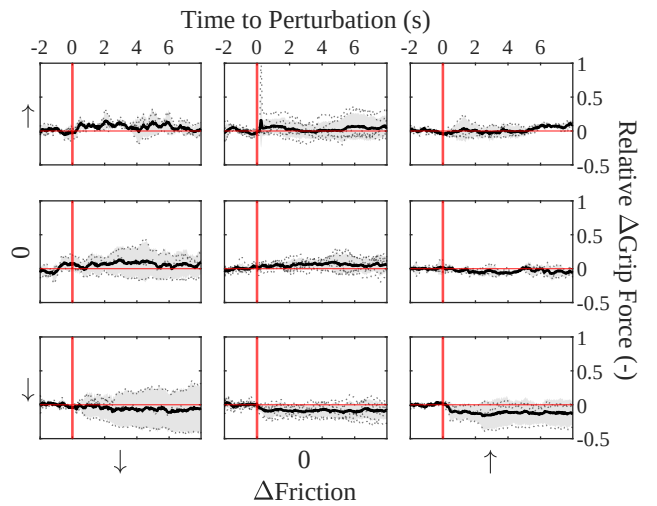
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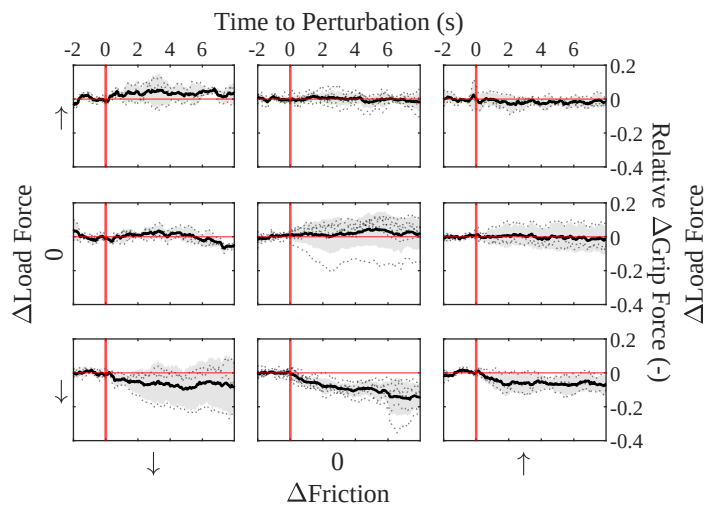
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P15 Lift Curves (N=36)**P16 Lift Curves (N=36)****P17 Lift Curves (N=36)****P18 Lift Curves (N=36)****P19 Lift Curves (N=36)****P20 Lift Curves (N=36)**

P1 Holding Curves (N=36)**P2 Holding Curves (N=36)****P3 Holding Curves (N=36)****P4 Holding Curves (N=36)****P5 Holding Curves (N=36)****P6 Holding Curves (N=36)**

P7 Holding Curves (N=36)**P8 Holding Curves (N=36)****P9 Holding Curves (N=36)****P10 Holding Curves (N=36)****P11 Holding Curves (N=36)****P12 Holding Curves (N=36)**

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P19 Holding Curves (N=36)**P20 Holding Curves (N=36)**