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Experimental study of the influence of friction and mass on finger pad mechanics during object lifting

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Abstract

On a daily basis, humans perform skillful manipulation tasks by properly adjusting their grip force to the diverse properties of an object. This continuous adaptation of the gripping behavior relies on the integration of an important amount of feedback by the central nervous system. Among these, tactile afferents, resulting from the complex mechanical deformations occurring at the fingertip-object surface, are encoded by mechanoreceptors, and are assumed to provide important information regarding surface properties. In addition, proprioceptive input presumably also contributes to accurate manipulation through muscle afferents.

To better characterize how humans adjust to different friction and weight conditions, 15 participants were requested to perform a lift-off task with a device enabling to record both the applied forces as well as images of the fingertip deformations. The friction, as well as the weight of the device were changed throughout trials to gain insight on the mechanisms allowing adaptation of behavior to a new condition. The results show that adaptation to friction solely relies on tactile afferents, whereas adaptation to weight seemingly benefits from multisensory integration, wherein proprioceptive feedback would constitute the main source of information.

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Chapter 1

Introduction

1.1 General introduction

Everyday we are required to accurately manipulate objects for our daily tasks. Hence, humans acquired efficient haptic behavior that is essential for our daily interactions with our immediate environment. These can vary from very basic manipulations to quite precise ones such as carrying an egg. These tasks often seem straightforward at first sight, but they actually require the contribution of many different factors.

Indeed, grasp control depends on an accurate force coordination in order to correctly grab the object without dropping it, but also to avoid damaging the object by squeezing it too hard. To do this, the brain integrates a significant amount of information, which mainly comes as sensory and proprioceptive information.

Among these, tactile and muscle feedback are assumed to play a crucial part during online control. Tactile afferents, arising from the complex skin movements occurring during object manipulation, are produced by the numerous mechanoreceptors innervating the glabrous skin of the fingertips. This allows the central nervous system to acquire information on the physical properties of a touched surface. [1] Without tactile feedback, people fail to maintain a stable grip as they do not succeed in reacting to unexpected perturbations in object load or surface friction. [2] Another key factor in online control of grasp is afferent feedback from muscle spindles, providing information about kinematics and muscle dynamics. [3]

Therefore, the elaborate mechanical interactions between the fingertips, the limbs and the manipulated object presumably provide a substantial amount of essential information to the brain. However, it still remains unclear how these events are perceived and how each sensory system contributes to the motor responses. This thesis aims at deepening the understanding regarding adaptation of gripping behavior to friction and to weight by measuring the force and skin responses in an active setup.

1.2 Finger pad properties and deformation mechanism

When fingertips come into contact with a surface, significant skin deformations will occur. However, the way the skin deforms is greatly influenced by the complex geometry of the fingertips. In fact, finger pads correspond to a composite layered material exhibiting nonlinear viscoelastic and anisotropic responses with regards to tangential loads. Stimulation of fingertip at low frequencies will thus lead to an elastic response, while higher frequencies will induce a viscous response. Furthermore, the fingertip skin also undergoes a skin stiffening effect for increasing tangential stresses, resulting from the rigid collagen fibers which are randomly coiled at rest, and are progressively loaded and reoriented when stress is applied. [4; 5; 6]

Beside this, it is important to note that the properties of the finger pad will influence its deformation as well. Accordingly, the mechanical properties of the fingertip skin significantly depend on skin hydration. For instance, a lower level of skin moisture will result in stiffer behavior of the finger and less stable grips. Another important fact is that the deformation shape and amplitude is sensitive to the direction of loading relative to the orientation of the fingertip ridges. Consequently, the fingertip skin locally behaves stiffer along the ridges than across them. [4; 5; 6; 7]

As aforementioned, loading of the fingertip through dynamic gripping tasks induces substantial skin deformations. The progress of imaging techniques enabled to observe the evolution in time of this phenomenon by means of high resolution images of the fingertip at the skin-object interface. The outcomes showed that fingerprint deformation during loading approximately behaves as predicted by contact mechanics of a homogeneous elastic sphere, as is depicted in Figure 1.1.

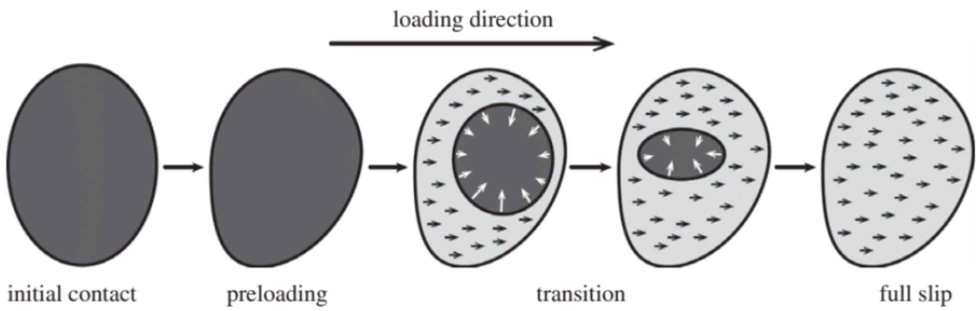

Figure 1.1: *Evolution of fingertip contact dynamics of slip under tangential loading. Scheme representing the different steps from initial contact to full slip. Taken from [4].*

In fact, when submitted to tangential loading, finger pad deformation arises through several stages. At first, when the finger comes into contact with the surface, initial contact is established. The cutaneous ridges of the finger coming into contact with the surface establish a contact area, which can be approximated by an elliptical region. As tangential stress progressively increases, the contact area will be modified due to tissue-rolling deformations. This is referred to as the preloading phase. Once the tangential force increases enough to counter the normal force, partial slip (also called incipient slip) emerges and gradually propagates from the periphery to the center of the fingertip during the transition phase. When the amount of stuck skin, i.e. non-slipping skin, reaches zero, fully developed slip is reached. Soon after the first moment of full slip, the displacement field becomes homogeneous, reaching a state called steady slip. [4; 5]

Hence, this stick-to-slip behavior has key implications regarding dexterous manipulation. Indeed, the deeper slip spreads inside the contact area, the less secure the grip will become as the contact gets closer to full slip. [8]

1.3 Precision grip and force control in object manipulation

Precision grip is a specific way of grasping objects with the index and the thumb that allows to perform accurate manipulations. It mimics a typical finger position adopted for classic grip tasks.[5] To grasp and maneuver objects without them falling, it is important to correctly adjust the applied forces to avoid full slip. The forces interacting with the object can be separated into two types: the grip force (GF) and the load force (LF), both illustrated in Figure 1.2A.

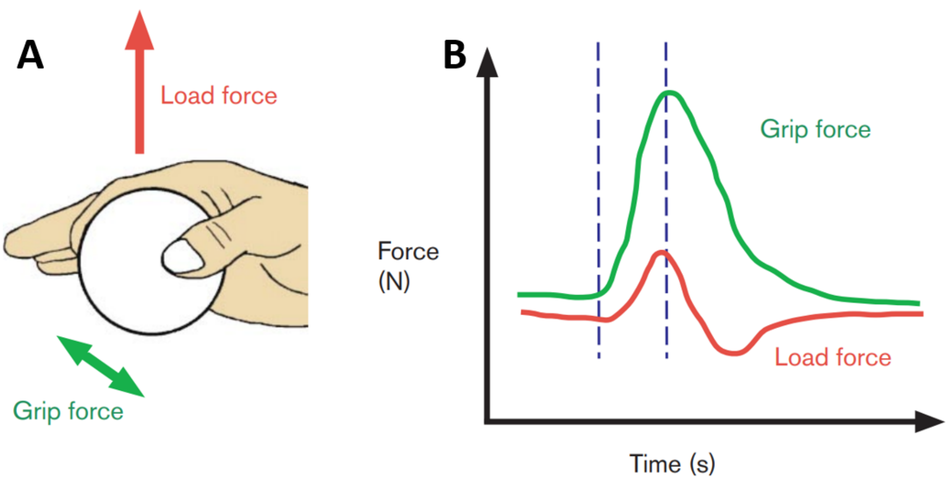

Figure 1.2: *A) Illustration of precision grip and the forces in play: the grip force and the load force. B) Coordination of these forces during movements. Taken from [9].*

The grip force corresponds to the normal force applied on the contact surface and prevents the object from slipping. On the other hand, the load force results from the norm of the tangential force components, namely the gravitational forces resulting from the mass of the object, and the inertial forces appearing when the object is set into motion. In order to perform successful object manipulation, grip force must be optimally adjusted to the load force to compensate for object weight and inertia. Nevertheless, friction at the fingertip contact also influences the required level of grip force, since it modifies the likelihood of slip to occur. Therefore, the applied normal grip force must always be greater than the minimal grip force needed to avoid slip, called slip force, which depends on the load force and friction. As shown in Figure 1.2B, grip force is thus continuously adjusted to the level of load force and the friction.[4; 9; 10; 11]

1.4 Previous studies

Since the different aspects of human haptic behavior and finger pad mechanics are not well understood yet, several studies have been performed the past few years in order to shed some light on the matter. This section resumes a non-exhaustive list of researches that have been conducted in that field.

In 2011, André et al.[4] studied the role of fingertip hydration during the transition from sticking to slipping. They discovered that hydration substantially impacts the contact mechanics by increasing the stability of the grip under hydrated fingertips. The study also highlighted that the skin moisture significantly impacts the frictional properties of the finger.

Later, the mechanics during the onset of the transition from stuck to slip state were analyzed by Delhaye et al.[5]. To do so, they performed an experiment where a robotic passive platform applied monitored stimuli of different directions (proximal, distal, radial and ulnar), under varying normal forces and tangential speeds to the fingertip. Besides measuring the contact forces, they also recorded skin deformations by optical means. Dual behavior of the finger pad was observed, such that the skin was soft and elastic under small constraints, but the increase of tangential stress induced a skin stiffening effect. In addition, they observed that the amplitude and shape of deformation is greatly influenced by the direction of stimulation. They concluded that the nervous system presumably collects information from these complex and patterned deformations by means of tactile afferents.

A more extensive study on finger pad strains under passive shearing was performed by Delhaye et al.[6] in 2016. During the experiment, the fingertip underwent various directions of strain, under different normal forces and speeds. The recording of high-resolution skin deformation images enabled to measure the evolution of surface strains with time. In accordance with their previous study, they noticed highly reproducible strain waves generating different levels of stretch, compression and shear in the contact area. These strain waves spread in a reproducible way from the periphery to the center.

In 2017, Crevecoeur et al.[3] performed several experiments to gain insight on the role of tactile and muscle feedback when perturbation of the fingertip occurs. To that end, they carried out fingertip loading experiments to investigate how peripheral simulations (with and without anesthesia) and task instructions affect motor response. The outcome suggested that separate sensorimotor circuits, characterized by different functions and latencies, are responsible for the disparate observed responses.

Later, the importance of partial slips for the anticipation of full slip was demonstrated by Barrea et al.[12] by performing psychophysical experiments where they evaluated the ability to detect incipient slips on a smooth transparent surface. They found that slip could be detected when about 48% the contact area was slipping, thus before the occurrence of full slip. Moreover, the results suggested that tangential stress is not a good indicator of partial slip as it depends on surface friction. These findings reinforce the assumption that partial slips provide information to the central nervous system during manipulation to allow corrective gripping behavior.

More recently, Delhaye et al.[13] developed an active set up allowing to explore the interactions between the finger and the object during active manipulation. The aim was to figure out the correlation between sensory information and online control, i.e. readjustment of grip force, trough the recording of the forces applied by the fingers, the movement kinematics and the skin deformations. As a result, it appeared that grip force readily impacts fingertip strain, generating less strains and fingertip rolling when higher force is applied. They also showed that active manipulation generates a significant amount of strain in the contact area, providing meaningful information to the central nervous system.

Thereafter, Schiltz et al.[14] investigated what aspects of sensory information allow us to perceive a difference in friction when manipulating objects, and accordingly quickly adjust our gripping behavior. To do so, subjects had to perform a grip-lifting task with the active set up. Images of skin deformations through the glass plates of different friction were recorded during the tasks. They observed adaptation of grip force depending on the friction as well as significant local differences in strain patterns in the contact area during the loading phase. The latter most likely triggering the adjustment of the grip force after an unanticipated change in friction.

Finally, Schiltz et al.[8] conducted an experiment to test whether humans use partial slip as an indicator of contact stability and exploit it to fine-tune their gripping behavior. The experiment consisted in point-to-point movements with the active manipulandum for different friction conditions. The results indicate that participants consistently adapted their grip force to the friction, resulting in a comparable amount of partial slip no matter the friction state. This implies that grip force seems to be adjusted in such a way that the level of partial slip remains under a certain upper bound across friction conditions, making it a key feature for active manipulation.

1.5 Goals of the study

This master thesis aims at observing and comparing the adopted behaviors when manipulating objects of different friction and mass. More precisely, the objective is to gain more insight on the mechanisms behind the adaptation to objects of different friction and weight occurring in our everyday life. To do so, subjects had to perform a lift-off task with different surface friction or weight conditions, being unaware that any changes were performed. The applied forces and fingerprint images were recorded, enabling to perform analyses on each condition.

Hence, this study falls within the framework of extending knowledge on the mechanisms allowing dexterous object manipulation. This has implications for the design of haptic interfaces and tactile displays which try to mimic the human dexterity. In other words, the end-goal is to figure out how human haptics work in order to create hand prostheses or other devices able to approximate real life manipulation behaviors, which are tremendously efficient.

Chapter 2

Methods

2.1 Set-up

This experiment was performed using the *ActiveTouch* set up, shown in Figure 2.1. The device weighs a total of 540g and is equipped with a force recording system along with an imaging system. It was specifically designed to be able to study the applied forces as well as to enable the characterization of finger pad deformations occurring at the contact area between the skin and the manipulated object. The latter was constructed to be manipulated through a precision grip, i.e. with the fingertips of the thumb and the index, and allows vertical (up and down) movements.

To be able to study the mechanics of finger pads in detail during active object manipulation, the apparatus has been equipped with key elements. Figure 2.1B shows a cut of the device in the direction of the plane shown in Figure 2.1A. At the top, the *ActiveTouch* device is equipped with an accelerometer allowing to record the kinematics of the object. In addition, each side of the manipulandum is provided with a six-axis force and torque sensor to measure the forces applied by each finger for each axis of the reference system displayed in Figure 2.1C. These signals were recorded with a frequency of 200Hz and were used to compute the grip and load forces during each trial. The device also comes with two removable glass plates, allowing to vary some physical properties of the manipulandum at the contact area, such as friction or roughness. It is on these glass plates that both fingers are placed in precision grip during the experiment. The vertical position of the manipulandum is measured through an optical measurement sensor.

For this study, in order to generate different levels of friction, two different types of materials were used to serve as glass plates. First, normal optically flat glass was used to produce the first type of glass plates, representing "high friction" plates. To create "low friction" glass plates, a nanoscale pattern was printed on the surface of the glass, thereby reducing the contact between the skin and the glass. Note that the difference between both glass plates is not noticeable by the human eye.

Recording the fingerprint mechanics at the fingertip-plate contact is possible through a custom optical system. This system is illustrated in figure 2.1D and is based on the principle of frustrated total internal reflection. The light, originating from the light source across from the recorded finger, is passing through a half-mirror to illuminate the finger. Parts of the light are then either reflected or transmitted by the contacting glass depending on the contact of the fingerprint with the glass. Indeed, when fingerprints are in contact with the glass, the light transmission index is increased resulting in less reflection and thus darker fingerprint images as illustrated in Figure 2.1E. A checkerboard pattern was also added on the glass plates to track possible glass displacements during the experiment. This system allows to record images at high resolution and with a speed of 100 frames per second.

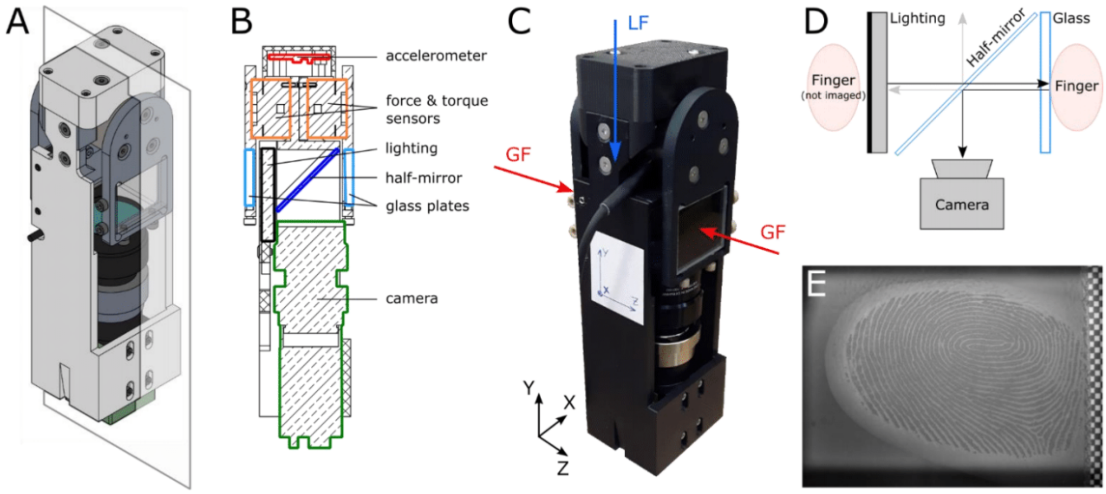

Figure 2.1: *Full description of the Active Touch device. A) Sketch of the complete manipulandum. B) Identification of the different elements constituting the device. C) Picture of the real-life manipulandum and establishment of the corresponding reference system and application of contact forces. D) Representation of the integrated optical system. The arrows depict the path of the light which ultimately allows to image the index at the surface of the glass plate. E) Example of observed fingerprint images, finger ridges in contact come off darker due to the decreased reflection of light. Taken from [13].*

2.2 Participants

The recruitment of the participants was based upon several criteria. They had to fit in the age interval, be right-handed or ambidextrous and be free of any motor or neuronal disorder that would affect their manner of manipulating objects. In addition, the fingertip skin of their index and their thumb had to present no significant damage, such as wounds, that could potentially bias the results.

In total, fifteen healthy participants (11 men and 4 women), aged between 18 and 35 years old, took part in this experiment.

Before the beginning of the experiment, each subject was given more information about the goal of this study and the protocol of the experiment. Each participant then provided its written informed consent by signing the consent form.

2.3 Experimental procedure

For this experiment, the *ActiveTouch* device was connected to a system of pulleys allowing to perform modifications of its weight. The initial weight (540g) was modified by a counterweight of either 210g or 320g. Therefore the apparent weight of the manipulandum could vary between either 330g (for the light counterweight) or 220g (for the heavier counterweight) during the experiment. The counterweight system was hidden by a black veil to prevent the subject from seeing any changes in weight.

Figure 2.2: *ActiveTouch manipulandum hold in precision grip. Taken from [14].*

Before starting the experiment, subjects were asked to properly wash their hands with soap and water and to let them air-dry in order to avoid any contamination on the fingertips. An explanation of the experimental protocol was given while their hands were drying. Once their hands were dried, they had the opportunity to get acquainted with the apparatus and learn how to manipulate it.

The general task that subjects were asked to perform during the entire experiment was a lift-off movement followed by a brief stabilization static phase. Sonor and visual signals were provided throughout the experiment to guide the subjects in their task. They stood in front of the set-up and they all manipulated the object with their right hand.

At the beginning of each trial, participants were asked to grab the manipulandum without lifting it. They were given ten seconds to correctly place their fingers (index and thumb), i.e. by holding the manipulandum in a precision grip on the glass plates (see Figure 2.2) and positioning the index in the middle of the image, and to stabilize their grip force at 1 N. The force signals and the fingerprint image were displayed on a screen in front of them. After those 10 seconds, sonor cues indicated the pace for the movement. More precisely, the participants had to lift the object to the upper visual cue, corresponding to a lifting distance of about 20cm, in 0.8 seconds. Once they reached the target, they had to stabilize the manipulandum for 1.5 seconds before putting the manipulandum down.

After each trial, the glass plates were cleaned with alcohol to ensure the same conditions throughout the whole experiment and to maintain a good image quality. At the same time, the second experimenter either changed the counterweight or acted as if he was changing something, so that the subject was not influenced by a difference in behavior. Between blocks, subjects received a short break at the opposite side of the room to prevent them from seeing the glass plate changes. Throughout the entire experiment, participants were requested to apply a minimal amount of grip force to manipulate the object. This was reminded at the beginning of each block.

The experiment consisted of twenty blocks containing six trials each. Between the blocks, pseudo-random changes in friction were carried out by switching the glass plates. Even when glass plates were not swapped, the duration of the short break remained the same so as not to raise any suspicions. For each block, the counterweight was changed either at trial number three, four or five in order to always have minimum two subsequent trials with a same manipulandum weight. The trial number at which the counterweight was changed in each block was determined in a pseudo-random way. The precise experimental protocol is outlined in Figure 2.3. Each subject was submitted to the same experimental procedure.

In total, each participant performed 120 lift-off trials, resulting in a total of 1800 trials (120 trials $\times$ 15 participants) performed in the context of this study. The total duration of the experiment was approximately two hours.

Figure 2.3: *Detailed experimental protocol, consisting in 20 blocks of 6 trials each (120 trials in total). Red boxes represent blocks with the low friction glass plats, blue boxes stand for high friction glass plates. The thickness of the contour of these color boxes depict the weight condition the block started with, thick contour stand for maximal weight of the object and thin contour stands for minimal weight. The smaller numerated boxes represent the trials individually. Grey colored boxes stand for weight catch trials. Each block contained at least one change in weight.*

At the end of the experiment, the friction coefficients of the subjects were measured for both glass plates. These measures were performed using the *ActiveTouch* device stabilized on the table. Participants were instructed to rub both their index and their thumb on the glass plates, performing up-and-down oscillations inducing complete slipping of the fingers. For each glass plate (the high friction and low friction glass plates), this procedure was repeated three times but with different levels of applied normal force: around 1N for the first time, followed by 3N for the second and 5N for the third. Subjects were able to monitor the applied force as it was displayed on a screen in front of them. No images were recorded during this procedure. [15]

2.4 Data analysis

The collected data signals were processed and analyzed using MATLAB. To perform analysis on this data, several previously elaborated MATLAB functions were used (from the LibactiveTouch, benutils and Imagetools toolsets). These codes were developed during the previous studies regarding the *ActiveTouch* manipulandum. The newly created functions within the framework of this master thesis are available on GitHub.

The measurements originating from the different sensors of the manipulandum were recorded at a sampling rate of 200 Hz. Hence, information about the forces, position and acceleration is available for every five milliseconds. In contrast, images of the fingerprints were recorded at 100 frames per second.

Double catch trials, i.e. trials containing both a friction catch and a weight catch at once (six in total), were excluded from the analyses due to insufficient data to support results.

2.4.1 Force analysis

As initial step of the analysis, a review of what is happening at the level of the applied forces was conducted. The recorded force and torque signals were filtered with a Butterworth filter (of fourth order), with a cut-off frequency of 20 Hz. The same filter was applied to position signals but with a cut-off frequency of 5 Hz to reduce noise on the position measurements as much as possible.

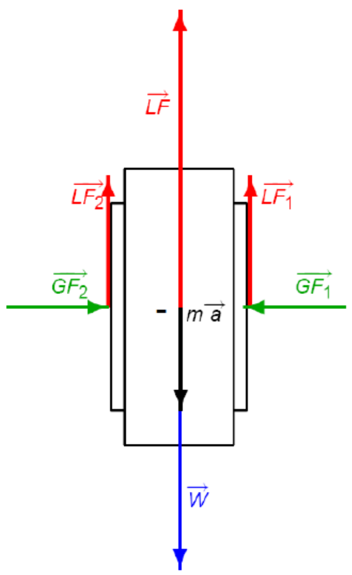

Figure 2.4: *Illustration of contact force components with regards to the ActiveTouch device: grip force components in green and load force components in red. Modified from [16].*

Recorded force signals for each axis of the aforementioned reference system were transformed into the two main force components, i.e. grip force (GF) and load force

(LF), shown in Figure 2.4. Those will be the main studied force signals and were computed in accordance with their definitions. Hence, the grip force, corresponding to the applied normal force, was obtained as followed:

$$GF = \frac{GF_{z,index} - GF_{z,thumb}}{2}$$

On the other hand, the load force results from the tangential forces caused by the weight of the object and its inertia. This is translated into the following relation, which is illustrated by Figure 2.4.

$$\begin{aligned} \overrightarrow{LF} &= \overrightarrow{W} - m \cdot \overrightarrow{a} \\ &= m \cdot \overrightarrow{g} - m \cdot \overrightarrow{a} \end{aligned}$$

As the force signals were recorded along a three axis reference system (see Figure 2.1), the tangential forces were categorized into two types: a horizontal component (LH_h, corresponding to forces applied along the x axis) and a vertical component (LH_v, corresponding to forces applied along the y axis). They result from the sum of the forces exerted tangentially by each finger in that given direction (either horizontally or vertically). The load force was then obtained by computing the norm of these components:

$$LF = \sqrt{LF_h^2 + LF_v^2}$$

Based on those definitions, a typical position, GF and LF curve as a function of time derived from a standard trial are shown in Figure 2.5. As stated previously, the grip and load force maxima peaks are aligned and occur at the very beginning of the lifting movement, i.e at the moment when the objects takes off. In addition, it can be seen that the lifting movement induces two load force peaks, one positive and one negative peak, respectively associated with the acceleration and deceleration stages induced by such a point-to-point movement. The deceleration phase is required because of the counterweight, inducing high inertia during the movement, which has to be stopped to enter the static phase.

Since the path followed by these load force, and consequently grip force curves, highly depends on the kinematics of the movement, all the trials were aligned in order to accurately perform global analyses. As a matter of fact, the kinematics slightly varied across trials and participants. Therefore, the coupled force curves were aligned on the moment the load force exceeds 2N. This corresponds to the earliest moment the subject could perceive a change in mass, as 2N is the static load force (when no movement is performed) associated with the lightest weight of the device. As a result, this point in time will be used as reference time for the subsequent analyses.

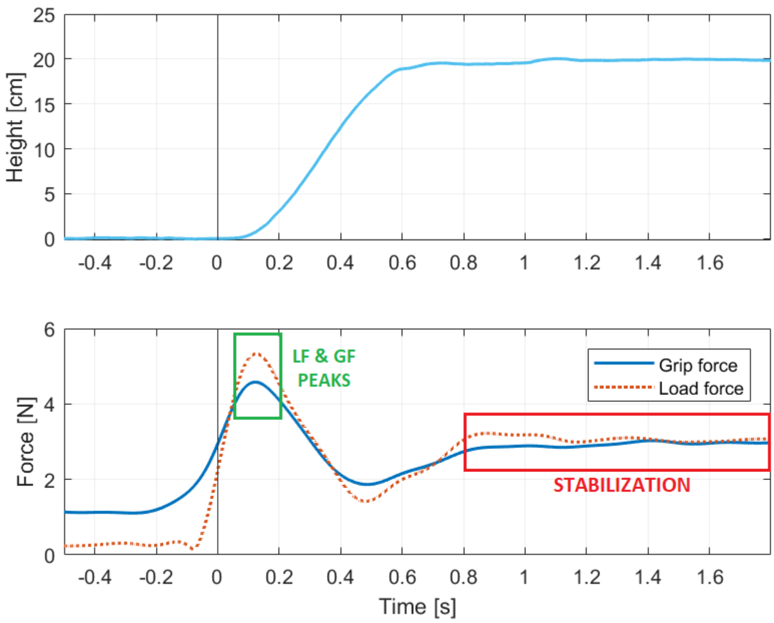

Figure 2.5: *Evolution of position, load force and grip force during a typical trial of a subject. The maximal load force and grip force peak is coupled and is indicated in green. The stabilization phase is depicted in red.*

2.4.2 Image processing

With regard to the image data set, processing of the recorded images was necessary to enable accurate evaluation of surface skin strains and slipping areas inside the contact area during the dexterous manipulation task. Since each trial consisted of two stages, i.e. a first phase for coming into contact with the glass and the subsequent lifting phase, images were cut so that only images of the second phase were kept. Indeed, given no motion occurred during the first ten seconds of the trial, the corresponding images did not contain valuable information for this study. Nonetheless, they could be used in the future to study the dynamics of establishment of fingertip-glass contact.

Image analysis was performed only on images presenting sufficient quality. Hence, two out of the fifteen participants were excluded due to bad image resolution. This resulted in a data set of thirteen participants for image analysis. As a reminder, images were recorded at a frequency of 100 fps, but for convenience, the frequency was reduced at 50 fps for the analyses. Image analysis consisted of several steps following a previously described method (Delhaye et al. 2014 & 2016) briefly summarized here.

As a first step, the apparent contact area contour, i.e. the region were the skin is in contact with the glass, had to be manually detected for a small subset of randomly selected frames (about 15 frames) for each participant. Subsequently, a machine learning algorithm was trained with those manually detected areas for each subject to extract the contact areas for the whole set of frames. As a matter of fact, the contact area is submitted to major anatomical differences between participants and will be reduced when the fingerpad is tangentially loaded.[4] It is therefore of high importance that these contours are detected with accuracy in order to allow proper image analysis. An example of contour detection is depicted in Figure 2.6A.

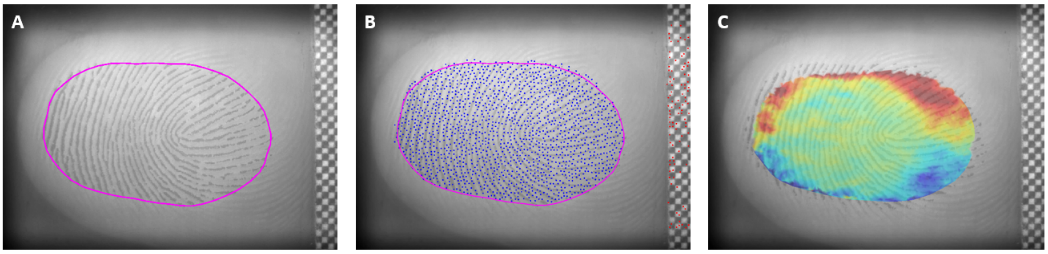

Figure 2.6: *Steps of analysis on fingerprint images. A) Detection of the contact area on fingerprint images, the contact area contour is shown in pink. B) Detection of the feature points in the contact area (blue points) which will be tracked along the movement to obtain a displacement field. C) Display of the computed strain rates, where blue represents compression and red represents tension.*

Afterwards, the displacement field was computed by using a computer vision technique. To do so, equally spaced optimal features were sampled in the contact area for three different moments of the trial: at the beginning, in the middle and at the end. This is shown in Figure 2.6B. This re-sampling of features for different time steps is crucial in order to cover the contact area during the entirety of the trial. These points were then tracked in the contact area from frame to frame using the optical flow method (described by Delhaye et al. 2014[5]), enabling the establishment of a displacement field between consecutive frames. The checkerboard added on the side of the glass plates allowed to spot potential movements of the glass that would bias the displacement field. If glass plate sliding occurred, fingerprint velocity was corrected by subtracting glass velocity, before moving on to subsequent analyses.

Finally, a Delaunay triangulation of the feature points was conducted in order to obtain displacement field gradients for each triangle. Based on these gradients, strain rate components were computed for three directions: axial strains given by ϵ_{xx} and ϵ_{yy}, respectively containing horizontal and vertical strains, and shear strain given by ϵ_{xy}. An example of typical strains observed during fingertip loading are displayed in Figure 2.6C.

$$\epsilon = \begin{bmatrix} \epsilon_{xx} & \epsilon_{xy} \\ \epsilon_{xy} & \epsilon_{yy} \end{bmatrix}$$

The physical meaning behind the strain rate components is a measure of the strain caused by the deformation of each triangle between two successive frames.

Strain rate norms were also computed with the intention of quantitatively measuring fingertip deformations, without regard for the type and direction of the deformation. This was done using the equation below.

$$\epsilon_n = ||\epsilon|| = \sqrt{\epsilon_{xx}^2 + \epsilon_{yy}^2 + 2\epsilon_{xy}^2}$$

Lastly, the displacement of the finger pad center, which is usually not deformed during manipulation, was also computed to detect potential slips. To do so, the total displacement of the feature points inside the contact area between the first and the last frame of each trial was computed. To retain displacement corresponding to the center of the fingertip, the value of the first percentile of total displacement was selected.

2.4.3 Statistical analysis

Statistical analyses were performed on temporal evolution curves in order to asses stages of the trials exhibiting significant differences between conditions. There were a total of twelve different conditions since two parameters were modified during the experiment, i.e. the friction of the glasses and the counterweight (2 friction conditions $\times$ 2 weight conditions $\times$ 3 types of trials (friction catch, weight catch or normal trials)). Accordingly, statistical tests enabled the detection of moments where catch conditions elicited a modification in gripping behavior.

The type of statistical tests carried out were generalized linear mixed-effect models. This choice was supported by the asymmetry of this experiment. Indeed, the number of trials in the different conditions is not equal. Moreover, due to the large variances arising across subjects, t-tests were not sufficiently accurate. Therefore, mixed-effect model was the best choice as it allows to perform accurate statistical tests between two conditions, even with missing and uneven data. In addition, it allows to take the variance between subjects in consideration and avoid presumably resulting bias. Given the significant size of the samples, statistical significance was attributed to a p-value below 0.001. All the tests were performed using the *fitglme* function on MATLAB.

Chapter 3

Results and discussion

This chapter is divided into several sections based on the type of analyses that were performed. The majority of them were performed on the whole data set, grouping all the participants. Hence if it is not specified that the reported results are for a single participant, then they represent total data across all subjects.

At first, data related to the coefficient of friction of participants is presented. Based on these data, individual friction coefficients are extracted to asses a difference in friction between the two types of glass plates for each participant.

Afterwards, the grip force is evaluated during the static phase for two cases: normal trials and catch trials. Hence, data from normal trials, i.e. trials where no change in friction or mass took place, are looked into in order to investigate if the subjects were able to adapt their gripping behavior according to the condition. Similar analyses are then be presented for the catch trials. They are defined as the first trials occurring after an unexpected change in friction or weight.

At a later stage, dynamics and kinematics of the lift-off movements are reviewed. To do so, temporal load force and grip force curves are examined to detect when the change in condition elicited an adjustment. To this end, catch trials were systematically compared to the normal trials in the condition preceding the catch. In addition, statistical tests were carried out to identify moments of significant difference in gripping behavior between conditions.

Acquired fingerprint images are then looked into to review what is happening at the fingertip-object interface. To begin with, a typical deformation pattern arising during a standard trial is depicted. Thereafter, temporal strain rate norm curves are analyzed to quantitatively asses skin deformation with time.

Finally, with the intent of clarifying some observations, the amount of full finger slipping and fingertip displacement that occurred for the different conditions is examined for each participant.

3.1 Coefficient of friction

Static coefficients of friction (μ_{static}) were determined for each participant based on the data extracted from the finger rubbing method explained in Section 2. From this acquired force data, the ratio of the tangential force to the normal force was computed for every full slip onset. This resulted in discrete data points exhibiting a nonlinear relation between friction coefficient and normal force. In fact, this relationship can be fitted by the following negative power law:

$$\mu_{static} = k(GF)^{n-1}$$

Since precision grip manipulation involves both the index and the thumb, the coefficients of friction were computed for both fingers on each glass type for each subject. However, the coefficients of friction usually remain similar for both fingers. As an example, Figure 3.1 displays the evolution of μ_{static} with normal force for the index of each subject individually.

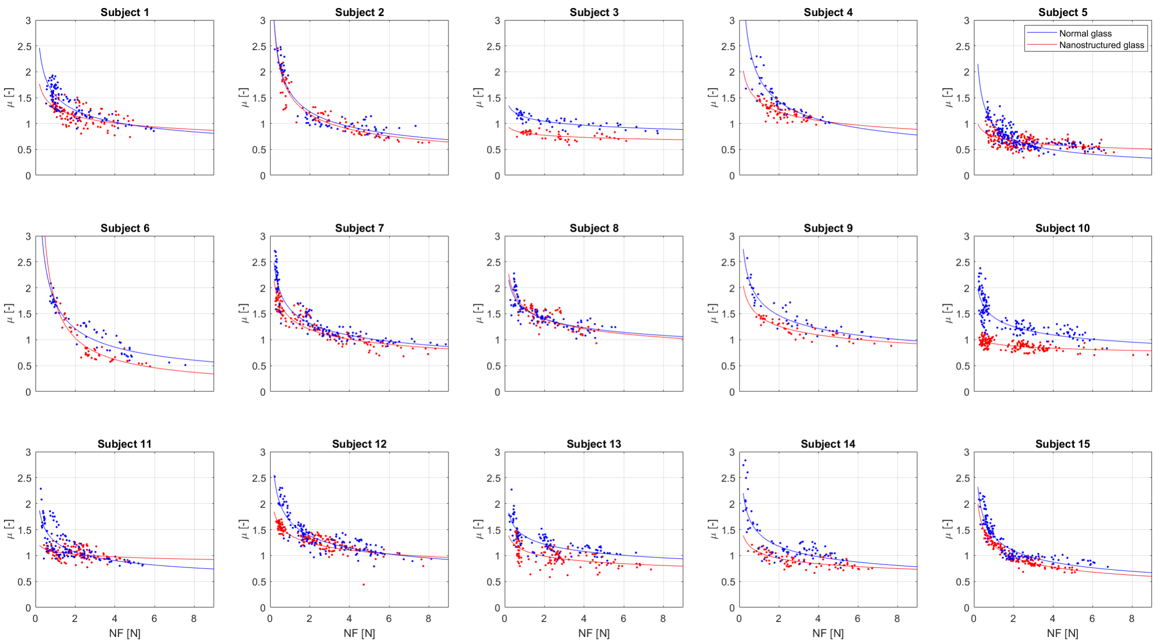

Figure 3.1: *Evolution of the coefficients of friction on both types of glass plates with normal force for each subject. Each subfigure displays the data points, computed as the ratio of tangential to normal force at full slip onset, for both normal (blue) and nanostructured (red) glass pates. The points are fitted by a negative power law.*

As first observation, it can be seen that overall, the coefficient of friction of normal glass tends to be higher than the one associated to nanostructured glass for the same applied normal force. This is relevant since the nanostructure should induce facilitated slip of the finger due to reduction of the real area of contact with the glass. For some subjects, the curves of the two types of glass plates cross and the friction coefficient of normal glass becomes smaller than the one for the low friction glass. This can be explained in two different ways. First, this intersection seems to occur when only very few discrete points were detected (generally for higher normal forces), which induced a more difficult establishment of the negative power law and could lead to a certain imprecision at those force intervals. Also, both coefficients of friction globally seem relatively close for most of the participants, leading to a more easy merge between the two curves.

Another observation that can be made is that the coefficients of friction follow the same trend across subjects. Hence, it decreases when grip force increases and tends to stabilize for higher values of normal force (around 5N), which is persistent with previous literature (Barrea et al. 2016 [15]).

Because part of this study focuses on the effect of friction on gripping behavior, sufficient difference in friction between the two glasses was required. Therefore, for each participant, the coefficients of friction were averaged between 1 and 5N, as this has been revealed to be the average range of grip force used for manipulation tasks [10]. Moreover, this range contains the largest number of detected points to compute friction in general, thus allowing the best quality of prediction. This average was computed for both the thumb and the index, in order to summarize the coefficient of friction of each subject by a single value. Relative differences in coefficient of friction between both types of glass were computed to quantitatively asses the difference in friction between the glass plates. The results are depicted in Figure 3.2. Participants with a relative difference below 10% were excluded for analyses regarding friction due to insufficient difference in friction. As a result, five participants were removed from the friction analyses.

Additionally, a color gradient was implemented as to rank participants in ascending order of relative difference in friction. Hence participants with a low difference in friction between the two glass plates are represented by blue color points which progressively turn red as the relative difference increases for the subjects. This same color code will be maintained for the following analyses.

The outcome indicates that the difference in friction between the normal glass and the nanostructured glass averages at about 15%. However, there is a large variance in relative differences across participants. It is important to keep in mind that even if summarized by a single point in this study, the coefficient of friction of finger pad remains a complex parameter that varies depending on several factors such as fingertip moisture and normal force. Consequently, friction most certainly fluctuates during the experiment, and these measurements do not exactly represent the real friction condition at the time of the different trials.

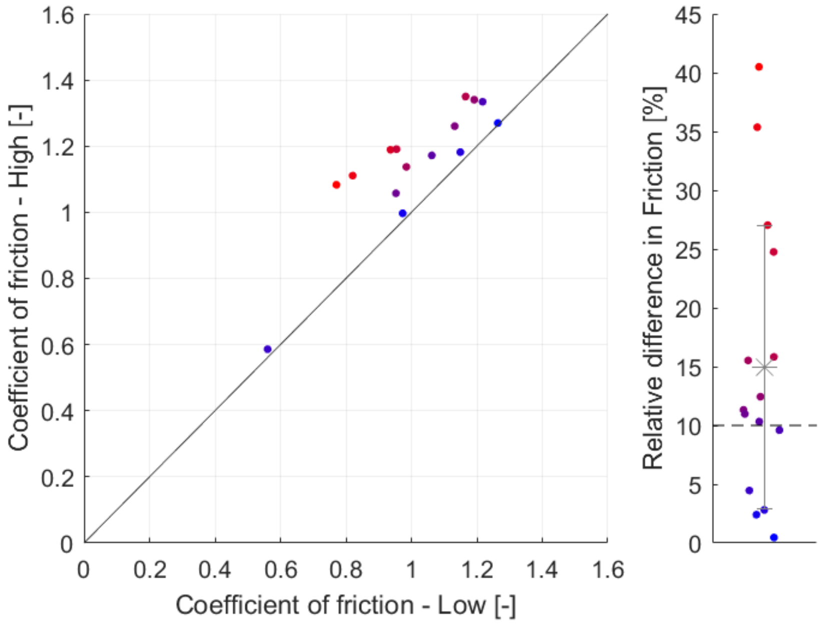

Figure 3.2: *Average coefficients of friction per participant (left) and relative differences in friction (right). Left: Each point represents the mean coefficients of friction for normal glass (high friction) and nanostructured glass (low friction) of each participant, averaged over manipulation GF range (1-5N) and over the thumb and the index. Right: Relative difference in friction between both materials for each participant. A color code is attributed as a function of the difference in friction: going from blue for low differences in friction to red for large differences in friction.*

Finally, it is interesting to note that, out of all participants, only two noticed some changes in friction.

3.2 Adaptation of grip force during normal trials

The aim of the second stage of analysis is to address the adaptation in gripping behavior induced by differences in friction or weight during normal trials, i.e. trials where the condition remained unmodified. Indeed, it is important to determine if the subjects were able to properly adjust their grip force to the condition (low friction or high friction, minimal or maximal weight). To do this, for each condition, the static grip force, i.e. grip force applied during stabilization phase, was averaged for each participant. To quantitatively asses the change in grip force induced by the examined parameter (friction or weight), the relative difference between opposed conditions was also computed. For this, the difference in GF between compared conditions was divided by the condition requiring the minimal GF, i.e high friction and minimal weight, to obtain relative differences between normal trials.

3.2.1 Adaptation to friction

First, the grip force applied under different friction conditions were compared to see if participants were able to correctly adapt to friction. Accordingly, they should apply more grip force during trials with the nanostructured glass plates as their surface is more slippery.

As depicted in Figure 3.3, the majority of subjects successfully adjusted their GF to friction. Hence, they applied slightly higher force during normal trials with the low friction glass plates. It can also be seen that the weight condition (minimal or maximal manipulandum weight) did not induce a considerably different adaptation in terms of GF. Indeed, the average relative differences between grip forces are of the same magnitude for minimal (7.80%) or maximal weight (9.31%). In addition, those relative changes in GF are comparable to the relative difference in friction previously determined in terms of level of magnitude.

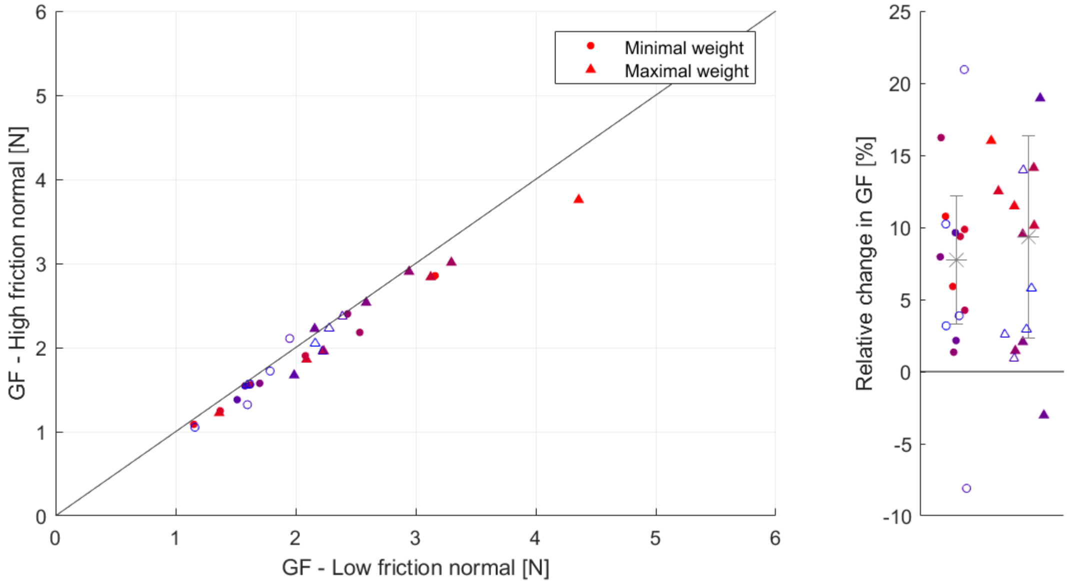

Figure 3.3: *Grip force adaptation to friction during the stabilization phase of normal trials. On the left, averaged static GF in each condition for each subject, represented by the markers. Points stand for trials performed under minimal weight and triangles represent trials under maximal weight. On the right, relative difference in mean static GF induced by a difference in friction under respectively minimal and maximal weight. The excluded participants, due to too low difference in friction, are represented by the empty markers, and are not included in means. Mean difference and variance represented in grey.*

A second observation is that relative change in GF induced by the differing friction of the glass plates does not evolve in parallel with the relative difference in friction coefficients throughout participants. Namely, participants with the highest measured difference in friction coefficients (represented by red points) do not automatically adapt their GF the most. This could be explained by the fact that friction is a complex concept relying on several factors. As previously mentioned, friction varies with time depending on moisture, which can fluctuate between different blocks but also throughout.[4] In fact, previous research reported that the moisture of fingers can significantly vary through trials, evolving towards an optimal level of moisture enabling a maximization of the coefficient of fiction.[17] This change in humidity comes from the production of moisture by the sweat pores of the skin when manipulating an object.[18] Also, the coefficient of friction depends on the applied normal force, as it is higher for lower normal forces. Therefore, the information about the coefficient of friction for each subject should be used carefully since it was probably not stable throughout the whole experiment. Moreover, excluded participants due to a lack of difference in friction do not seem to adopt a markedly different gripping behavior overall.

Ultimately, a last observation that can be made is that there is substantial variance in the levels of GF applied by the subjects. Even though the GF was higher for the heavier object weight in general, the amount of GF used during the static phase widely varied between subjects.

3.2.2 Adaptation to weight

Subsequently, the same analysis was performed for normal trials by comparing, this time, the applied grip force for different weight conditions. The results are shown in Figure 3.4.

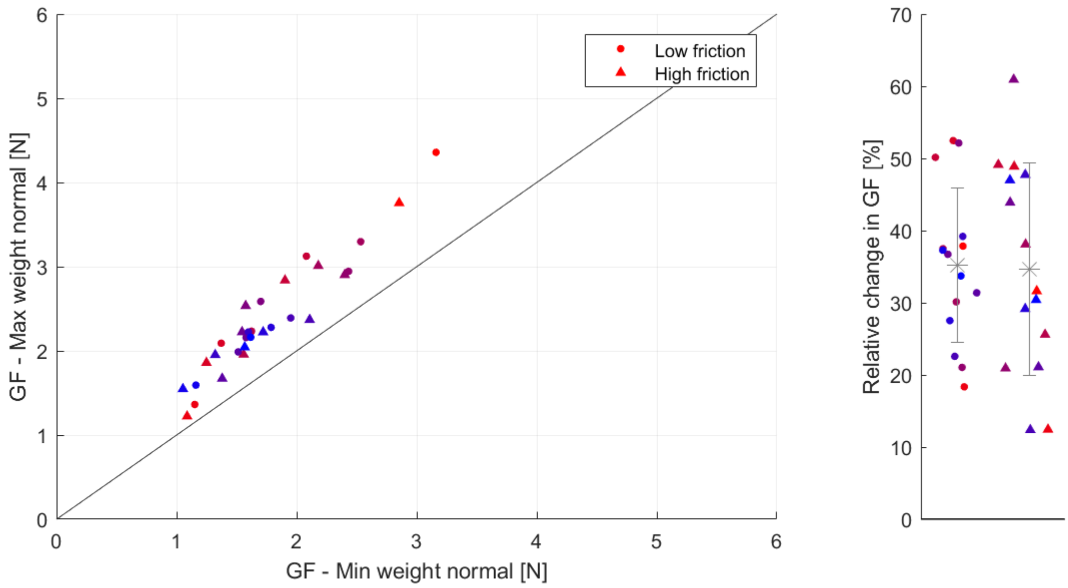

Figure 3.4: *Grip force adaptation to weight during the stabilization phase of normal trials. On the left, averaged static GF for each weight condition for each subject. Points stand for trials performed under low friction and triangles represent trials under high friction. On the right, relative difference in mean static GF induced by the difference in weight under respectively low and high friction. Mean difference and variance represented in grey.*

The figure reports an explicit adaptation to weight of all subjects throughout the static phase of the normal trials. Indeed, as expected, subjects increased their GF when the manipulandum was heavier. Also, the different friction conditions do not seem to induce differences in adjustment behavior since the mean relative differences are similar: 35.09% of relative difference in GF under low friction, and 34.57% under high friction. Note that twelve out of the fifteen participants noticed modification in weight.

In short, by comparing these results, it seems that weight leads to a more significant change in GF (about 35% of difference) than friction (about 10%) during the static phase. This suggests that weight would induce a stronger signal than friction, which is plausible since friction is only detectable by sensory signals while weight can benefit from a combination of both sensory and proprioceptive feedback.

3.3 Adaptation during catch trials

Once it was established that subjects adapted to friction and weight during the static phase of normal trials, catch trials were investigated. In first instance, GF during stabilization of catch trials were compared with the stabilization GF learned during preceding normal trials (under the opposite friction or weight condition). The aim of this comparison was to test whether adaptation already takes place during the first movement in a new condition, i.e a catch trial. As a reminder, four different conditions were possible: minimal weight under low friction, minimal weight under high friction, maximal weight under low friction and maximal weight under high friction.

3.3.1 Friction catch trials

Two types of friction catch trials were possible: either trials where the subject had been adapting to high friction and was then unexpectedly submitted to low friction, which will be called "catch low" for the upcoming analyses, and trials where subjects adapted to low friction before being exposed to high friction, called "catch high". Relative differences in GF between the condition the subject had been getting used to and the following catch were computed. Figure 3.5 displays the results.

As shown by Figure 3.5A, although not all participants adjusted correctly, catch low trials triggered an increase in GF that was already noticeable during the stabilization phase of the catch trial. This is explained by the fact that a catch low generates a higher slipping risk due to the sudden decrease in friction at the surface, leading to an increased risk to drop the object. Hence this type of catch necessitates an urgent increase in GF. The magnitude of the observed GF adaptation averaged at 9.07% under minimal object weight and 20.06% under maximal object weight. The adaptation to catch trials, reflected by the relative difference in GF, thus shows a similar level as for repeatedly practiced normal trials (Figure 3.3). These results are in line with previous results studying the effect of sudden changes in friction during active object manipulation [14].

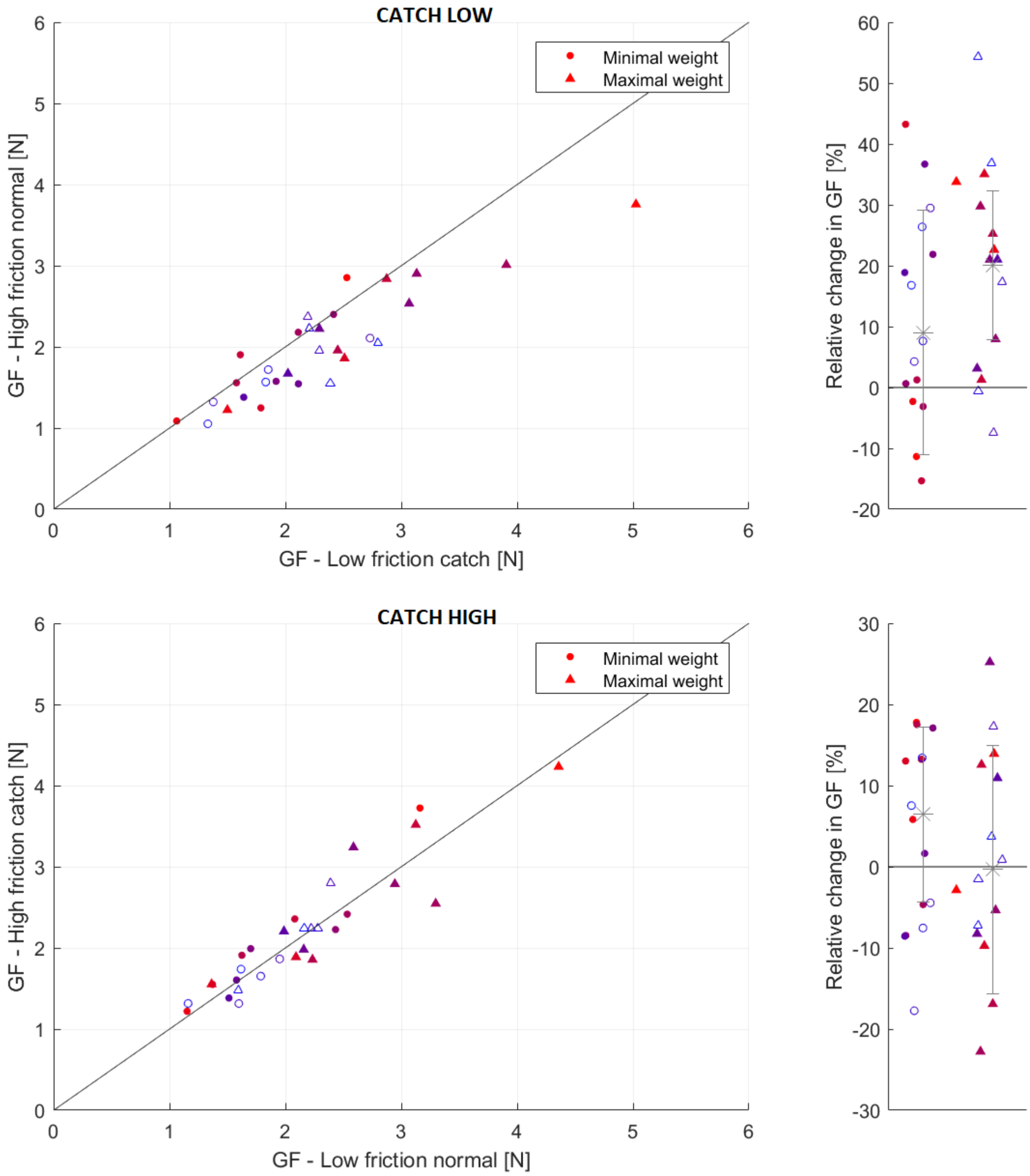

Figure 3.5: *Grip force adaptation to friction during the stabilization phase of catch low and catch high trials. On the left, mean static GF of the preceding normal trials is compared with the static force during the first period of stabilization for the catch trial. On the right, relative change in mean static GF induced by the catch trial. The minimal and maximal weight conditions are represented respectively by dots and triangles. Excluded participants are represented by empty markers.*

Additionally, these results suggests that object weight influences the level of adjustment to friction during catch trials. Indeed, higher weight induces a more pronounced adaptation, which can be explained by the fact that higher object weight involves an even higher risk of slippage, enhancing the need to adapt.

On the other hand, adaptation of static GF to catch high trials (Figure 3.5B) was far less pronounced. This probably results from the reduced risk of slip induced by such a catch trial. Indeed, the switch from a low friction condition to higher friction, causing lower risk of slippage, induces a less urgent need for adaptation to the new friction condition. Hence, the results show no clear indication of adaptation to the friction condition, with a relative change in static GF of 6.39% under minimal weight and -0.35% under maximal weight.

Just as for normal trials, the change in grip force induced by a modification of friction is not proportional to the difference in friction coefficient of the participant. At first sight, there does not seem to be an optimal adaptation of GF depending on difference in friction coefficient. Nevertheless, the same remark as for normal trials can be made, stating that there is a certain degree of uncertainty around the coefficient of friction as it can fluctuate given several factors.

It is however important to note that the data for friction catch trials originates from only few trials of the experiment. In fact, the number of trials per participant for the different types of friction catches ranges between 1 and 3 trials. The results are thus based on a fairly small amount of data, probably inducing some bias. Therefore, it is interesting to identify tendencies, but it is important to keep in mind that some deviations from expected behavior can be explained by the low amount of data to support these results. In addition, as friction catches always happened on the first trial of a new block, the data could also enclose the effect of the first trial following a short break. Indeed, previous studies reported an excessive amount of GF applied on the first trials of new blocks compared to the subsequent trials, for which GF progressively decreased.[13; 14]

In other words, gripping behavior would be influenced differently by friction depending on the associated risk: friction affects the static GF when the risk of slippage increases, but not when friction decreases, lowering the risk.

3.3.2 Weight catch trials

The same approach was used for weight catch trials, for which two types were possible: catch trials where the subject was suddenly submitted to minimal weight, following exposure to maximal weight, referred to as "catch min", and trials where they adapted to minimal weight before being unexpectedly exposed to maximal weight, called "catch max" trials. Figure 3.6 showcases the results of the comparison of GF during static phases between weight catch trials and preceding conditions.

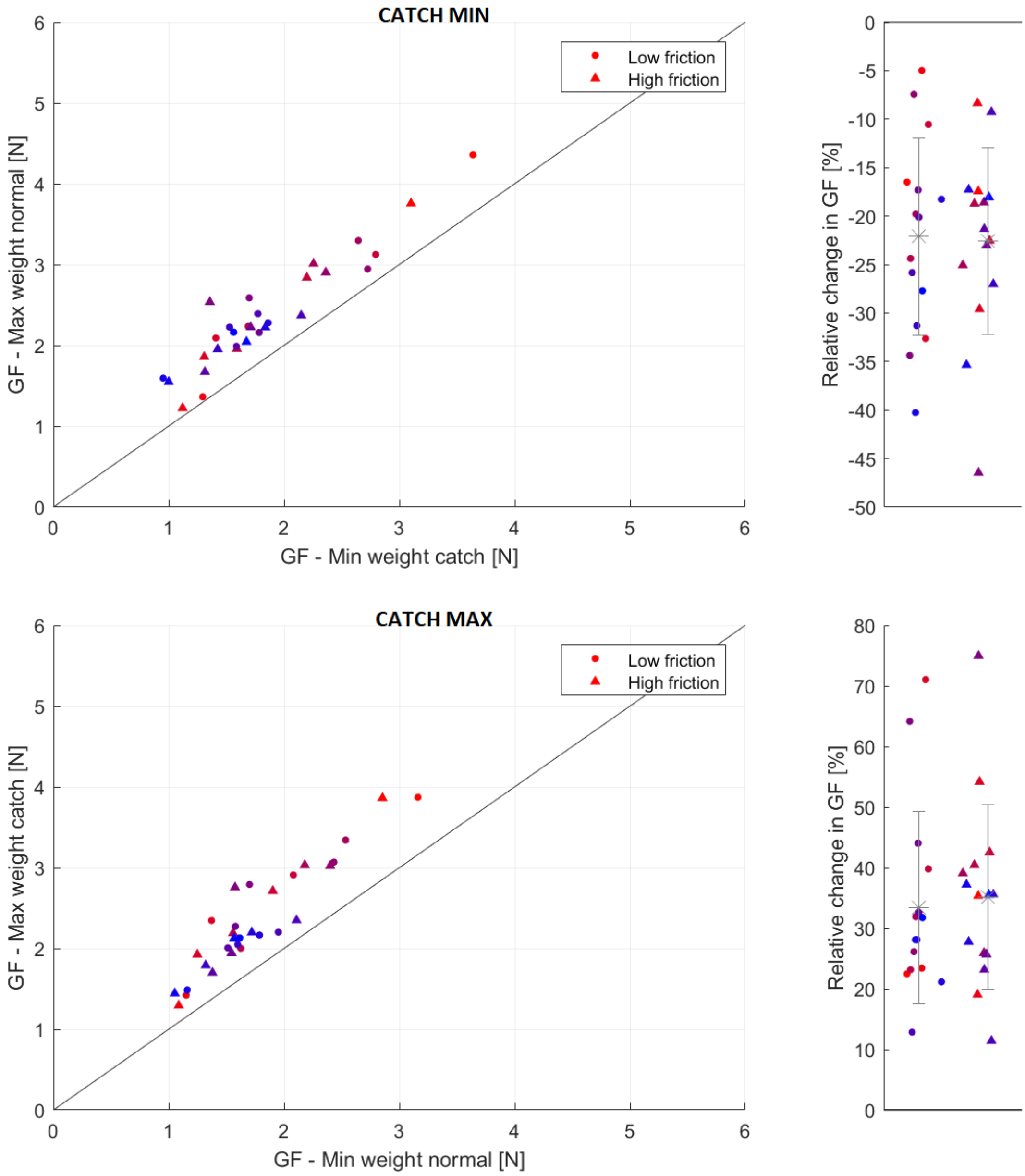

Figure 3.6: *Grip force adaptation to weight during the stabilization phase of catch min and catch max trials. On the left, mean static GF of the preceding normal trials is compared with the static fore during the first period of stabilization for the catch trial. On the right, relative change in mean static GF induced by the catch trial. The low and high friction conditions are represented respectively by dots and triangles.*

The results indicate that, for both types of weight catch trials (catch min and catch high), the participants already correctly adjusted their GF during the static phase by applying higher GF for the heavier manipulandum. The level of adjustment, evaluated by the relative change in static GF, for catch min trials (Figure 3.6A) averaged at -22.00% under low friction and -22.53% under high friction. Thus, participants already decreased their GF by about 20% during the first trial when object weight was reduced. This corresponds to a similar level of adaptation as for normal trials if they were computed relative to GF under maximal weight.

On the other hand, catch max trials (Figure 3.6B), during which the weight of the device increased, induced higher changes in static GF, with a change of 33.25% under low friction and 35.12% under high friction. Indeed, for catch high trials, the real relative difference in weight was of 55%, since the object switches from its minimal weight to its maximal weight, while a catch low resulted in a weight difference of 36.67%. However, note that these values represent the tangible change in weight, but a same level of GF adaptation could not necessarily be expected as it would imply that there is a strictly linear relationship between real weight and GF.

In short, the analysis of catch trials revealed that the adaptation to friction and weight during stabilization is different. Indeed, although friction catch trials did show some impact on the GF, namely for catch low trials, the expected change in behavior was not always observed. On the contrary, weight catch trials induced more pronounced GF adaptation with higher accuracy regardless the type of weight catch. This supports the previously mentioned assumption that weight induces stronger signals than friction.

3.4 Evaluation of dynamics and kinematics of trials

Having established that participants were already able to adapt their GF to drops in friction and to weight during stabilization of the first trials under a new condition, the temporal evolution of force curves was examined to detect when readjustment in gripping behavior appears. Both load force and grip force curves were looked into in order to evaluate both kinematics and dynamics of the gripping task.

As a reminder, all the curves were aligned on the moment the load force exceeds 2N. This corresponds to the earliest moment the subject could perceive a change in weight, because either the manipulandum would take off whereas normally it did not yet (if the weight was decreased), or either because the object does not take off while it should (if the weight was increased). This moment was chosen as reference point, and is therefore set as the time 0 for the upcoming analysis.

It is however important to keep in mind that even though it corresponds to the earliest moment participants can perceive a change in weight, a change in friction could be discerned earlier. Indeed, the participant already comes into contact with the glass plates during the first phase of each trial for the establishment of proper contact. Subjects were given 10 seconds to correctly place their fingers on the glass plates, but this operation took a variable amount of time across trials. It can be estimated that proper contact was established between 1 to 8 seconds in general before lifting. As of that moment of entering in contact with the surface, information could be perceived about the friction properties of the object. It is not certain whether the brain already collects some information about friction during that phase of simple contact, however as soon as tangential force appears and that the LF becomes nonzero, information about friction can be extracted.

This section systematically compares LF and GF curves of a catch trial with the preceding condition to which the subject adapted. In addition, the evolution of the relative difference in LF and GF between the two compared conditions are examined to determine moments of shifts in gripping behavior. Statistical tests (generalized mixed effect model) were performed at each time step (every 0.005s) to determine if the difference between the two conditions is significant by computing the p-value. This procedure also allowed to identify the first moment of significant difference in the way of manipulating the device between conditions.

3.4.1 Friction catch trials

The first step of the analysis for friction catch trials consisted in comparing the load force curves in order to make sure that subjects performed the task with similar kinematics regardless of the change in friction. As expected, the movements presented comparable kinematics throughout the different friction conditions. Indeed, as shown in Figures 3.7A & B and 3.8A & B, the average LF curves of friction catch trials approximately follow the same paths as the LF curves of the preceding condition. In addition, the low variance associated with those curves supports the statement that kinematics were similar between the friction catch trials and the prior normal trials.

For catch low trials, depicted in Figure 3.7, it can be observed that the GF curves associated to the catch progressively diverge from the normal trials, especially when the manipulandum was heavier (Figure 3.7A). As explained earlier, this presumably originates from the higher risk of slip elicited by a heavier object.

The results of statistical analyses indicate that a significant difference in GF of 12.93% is reached 95ms before the reference moment, i.e. when the LF exceeds 2N, for a catch low under maximal manipulandum weight. That is 383$\pm$132 ms after the beginning of the lift-off signaled by the sonor cue. However, this result must be carefully interpreted. Indeed, significance is found much earlier than in previous studies, where it appeared about 50ms before the LF peak at earliest. [14] There are two possible explanations for this. A first reason could be that significance in GF is reached earlier due to the established contact with the glass several seconds before actually starting the movement, whereas in the previous study, subjects did not properly establish contact prior to lifting the object. This period of contact with the surface of the object could potentially already give some information about friction and in consequence, generate a predictive adaptation in GF. Conversely, this detected significant difference could also result from a difference in applied GF during the contact establishment prior to lifting the object. Participants were instructed to

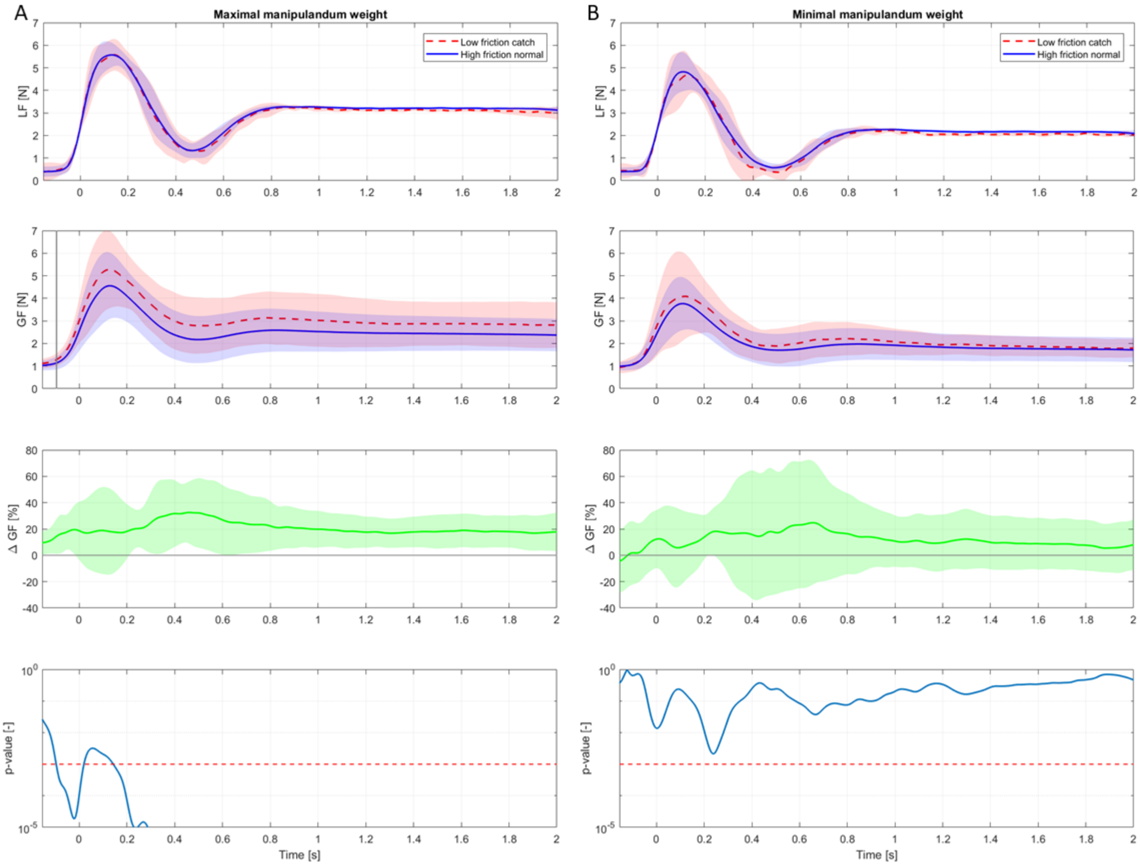

Figure 3.7: *Force adaptation to friction throughout the first movement of low friction catch trials. Temporal evolution of the LF, GF, difference in GF and p-value between GF curves during the first movement of A) low friction catch trials under maximal manipulandum weight, B) low friction catch trials under minimal manipulandum weight. The curves are aligned on the moment the LF exceeds 2N. The lines represent the means across participants: dashed red lines correspond to low friction catch trials and blue continuous lines correspond to normal trials under high friction. Shaded areas stand for the variance across means of participants. The p-value results from statistical tests performed on GF curves at each time step. Grey vertical line depicts the first moment of statistical significance. Dashed red line shows the threshold for statistical significance, put at $p<0.001$.*

apply 1N during that phase, but it is likely that subjects were not always precisely at 1N right before starting the lift-off, which could then bias the results. Although it is difficult to determine with certainty which explanation is the right one, the evolution of the p-value associated to those GF curves suggests that meaningful significance is reached only around 150ms after the reference point as long-term substantial difference in GF is revealed after that moment. That would correspond to 628±132ms after the beginning of the sonor cue.

For catch low trials under minimal manipulandum weight, no moment of statistically significant difference was found. Nevertheless, the mean GF curves show the same tendency as for catch low trials with a heavier object, but with a less pronounced effect.

Regarding catch high trials, Figure 3.8 shows that no significant changes in gripping behavior happened. Although a moment of statistical significance was detected for catch high under minimal manipulandum weight (Figure 3.8B), this result should not be considered as it is not relevant. Indeed, the p-value only reaches significance for a very short moment before increasing. The significant difference in GF is thus punctual but not maintained for the rest of the movement. Moreover, the depicted change in GF is not accurate as it shows an increase in GF while the opposite phenomenon is expected for an increase in friction.

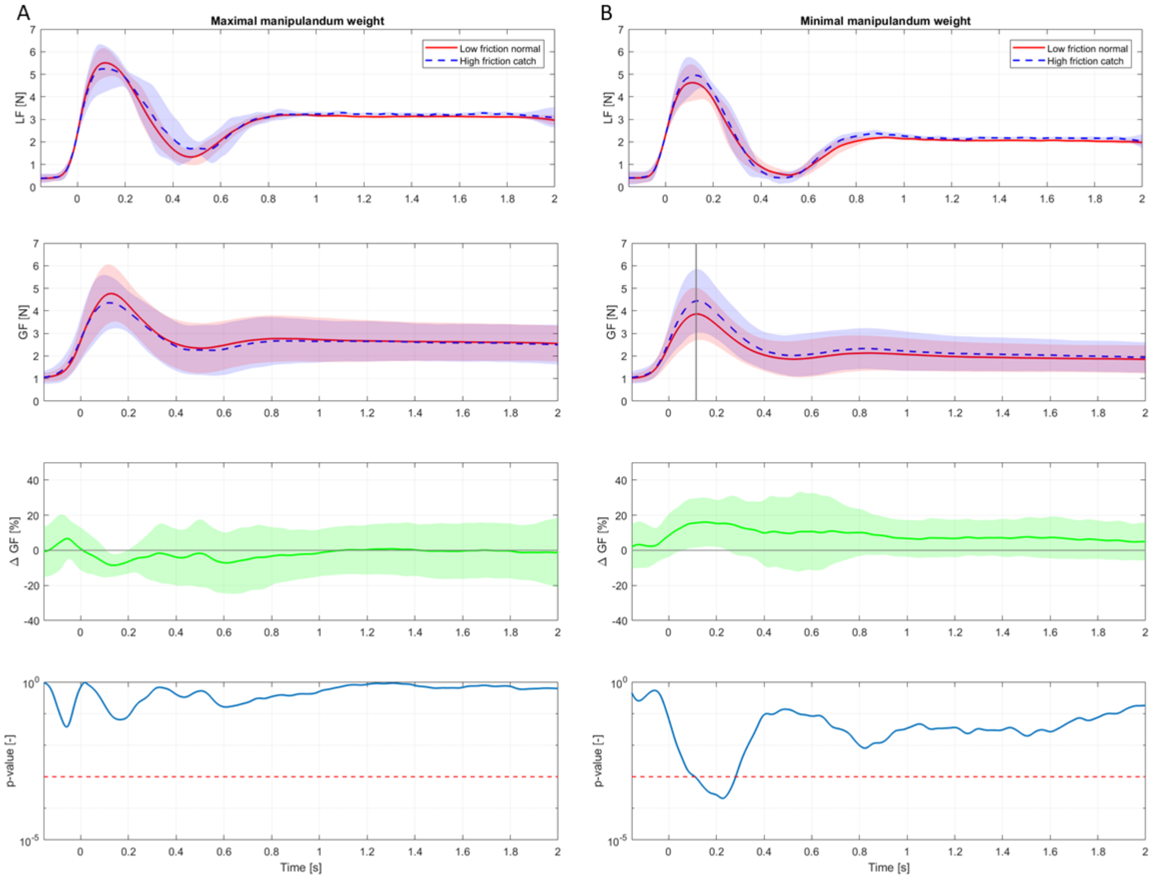

Figure 3.8: *Force adaptation to friction throughout the first movement of high friction catch trials. Temporal evolution of the LF, GF, difference in GF and p-value between GF curves during the first movement of A) high friction catch trials under maximal manipulandum weight, B) high friction catch trials under minimal manipulandum weight. The same explanations as for Figure 3.7 apply.*

Consequently, the results suggest that the reaction to a change in friction is not symmetrical, since GF was correctly adapted for catch low trials, but not for catch high trials, where almost no specific difference in GF was depicted. Additionnally, note that previous research observed a peak in ΔGF at the moment of the maxima of LF, which is relevant as this corresponds to the moment with the highest risk of slip. [8] However, although the mean curves and their variance show signs of this tendency, no real peak in GF difference can be identified.

Lastly, it should be reminded that these results for friction catch trials are derived from few trials. This could thus lead to a certain bias of the results which should thus be examined thoughtfully. Moreover, it has been reported previously that, whatever the friction of the glass plates, subjects had a tendency to apply a little more GF at the beginning of contact for the first trials following the short break, namely friction catch trials.[13; 14]

3.4.2 Weight catch trials

Weight catch trials were analyzed using the same approach. Therefore, the load force curves, depicted in Figure 3.10, were examined first. However, an important fact is that a weight catch consists in changing the mass of the manipulandum by means of a counterweight. Hence, it is critical to thoroughly consider what happens during such changes at the level of movement kinematics and dynamics. As expected, the results show that the LF was substantially impacted after an unanticipated change in weight (and thus also in counterweight).

During weight catch trials, since weight is changed by adding or removing a counterweight, this also induces modifications of the inertia of the device. Indeed, if a heavier counterweight is attached on the other end of the system of pulleys, the object will be lighter, but the inertia will increase. Accordingly, a lighter counterweight results in a heavier object with less inertia. To assess the magnitude of the effect of inertia on the movement kinematics, temporal acceleration curves were computed. These are shown in Figure 3.9 for the different types of weight catch trials.

As a matter of fact, the higher inertia resulting from a heavier counterweight could impact the kinematics, by causing more pronounced acceleration (when the object takes off) and deceleration (when the object is stabilized) phases. Acceleration with time was obtained by derivation of the position of the device, which was recorded by a laser system with regard to the position of the counterweight. Some inaccuracies possibly occurred due to motions of the counterweight during the movement, resulting in some unexpected values of acceleration. Therefore, an interpolation was performed in order to extract global tendencies of the curves. Nonetheless, results show that the acceleration curves are rather similar across conditions, suggesting that subjects tended to adjust their behavior to compensate for the change in inertia. Additionally, the distance between LF maximum and minimum peaks were also computed for each type of trial to study the effect of change in inertia on kinematics. The outcomes consolidated the observation that subjects tended to keep the same kinematics throughout trials, regardless changes in inertia.

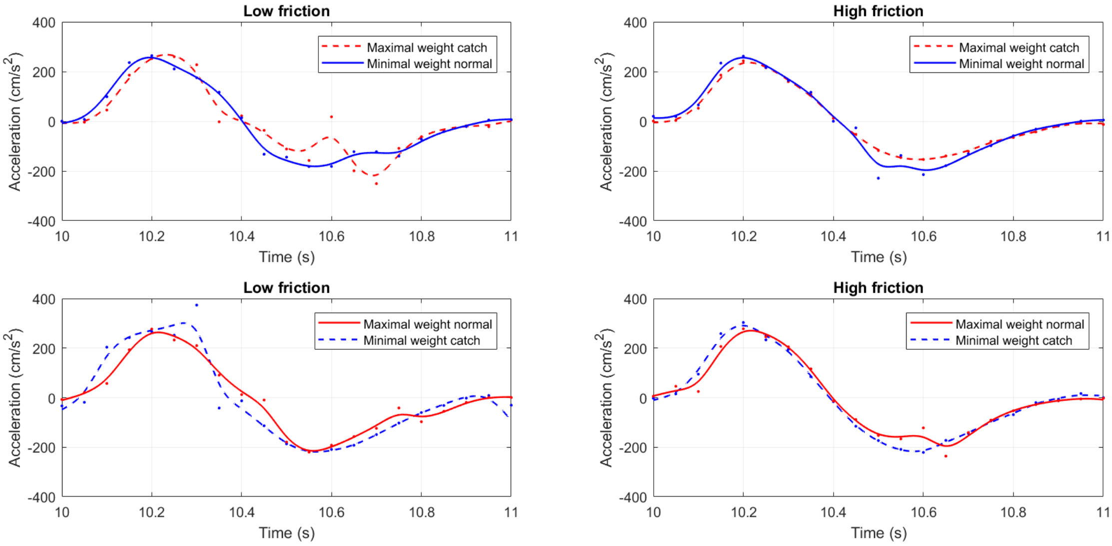

Figure 3.9: *Comparison of movement kinematics across weight catch trials. Evolution of the acceleration of the manipulandum as a function of time for the first movement of weight catch trials. Acceleration data points computed by derivation of mean position across subjects on intervals of 0.05s. The curves correspond to the interpolation of these data points to obtain global trends of the acceleration. Red curves stand for maximal weight, blue is for minimal weight. Continuous lines represent normal trials and dashed lines are for catch trials.*

Even though it was demonstrated that the kinematics of the trial did not vary much between catch and adapted trials, Figure 3.10 illustrates that LF curves still showed substantial differences from very early in the movement. This results from the fact that load force arises from both a component linked to the weight of the object and an inertial component. Therefore, a heavier object induces higher LF due to its greater weight. However, during the lift-off movement, the difference between catch and normal curves remains lower than could be expected for such a difference in weight. This can be attributed to the opposite change in inertia resulting from a change in weight, i.e a decrease in weight generating an increase in inertia and vice-versa. Hence, there seems to be some compensation between the weight-associated and the inertial components of the load force during the movement.

Another observation is that the relative difference in LF reaches a maximal value at the moment of the minimum peak of LF curves, regardless of the type of catch. This is relevant as it corresponds to the moment the manipulandum has to be slowed down and immobilized, hence compelling the subject to overcome the inertia of the device. The reason the difference in LF is globally higher in the case of catch max trials is because the relative change in apparent weight is higher than for catch low trials. Indeed, catch max trials induce an increase in weight (which corresponds to

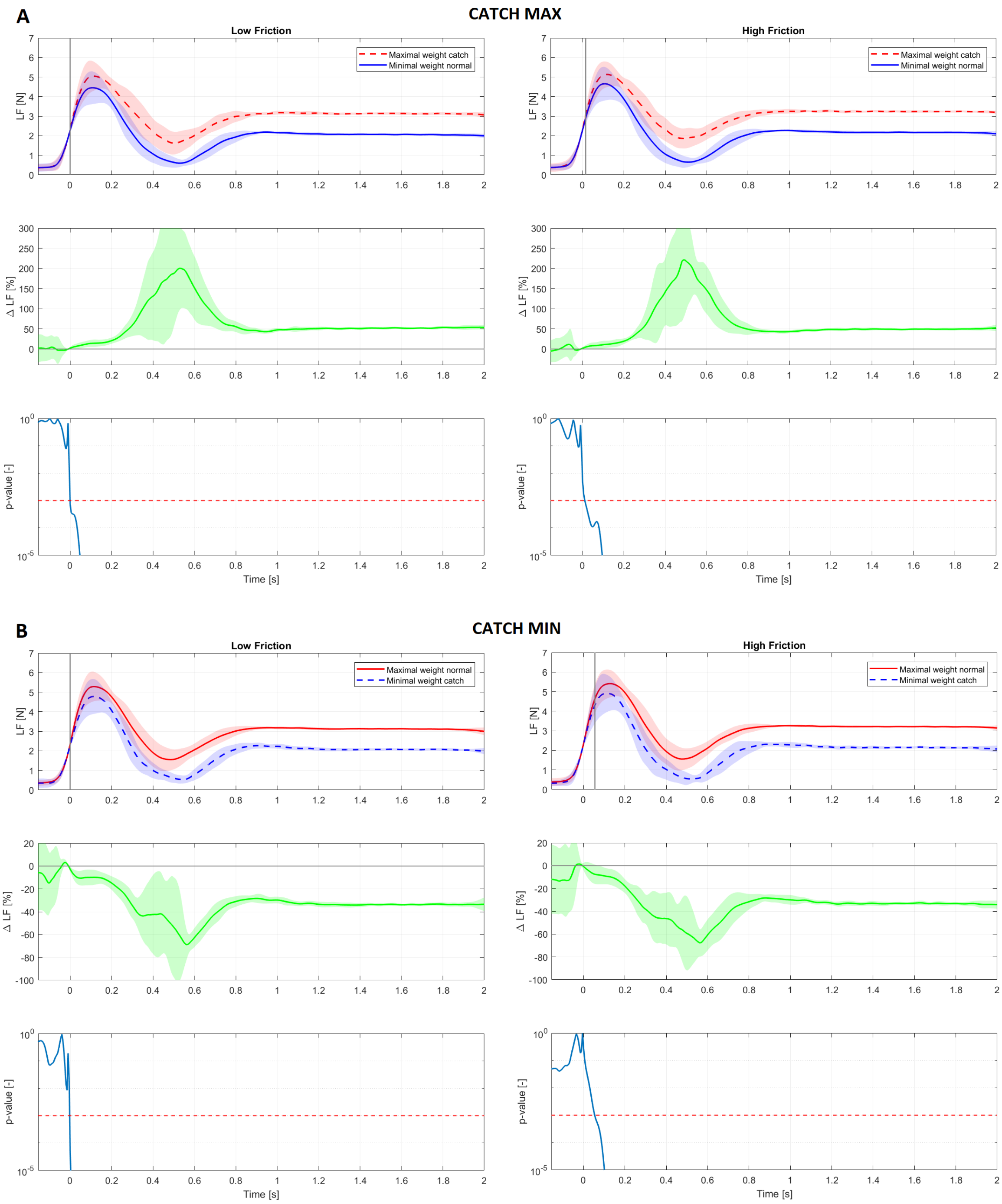

Figure 3.10: *Evolution of load force, difference in LF and p-value during the first movement of A) catch max trials under low (left) and high friction (right), B) catch max trials under low (left) and high friction (right). The same explanations as for previous similar figures apply.*

the static LF) of 55%, while catch low trials decrease the weight of 36.67%. This is confirmed by the values the differences in LF plateau at during the static phases.

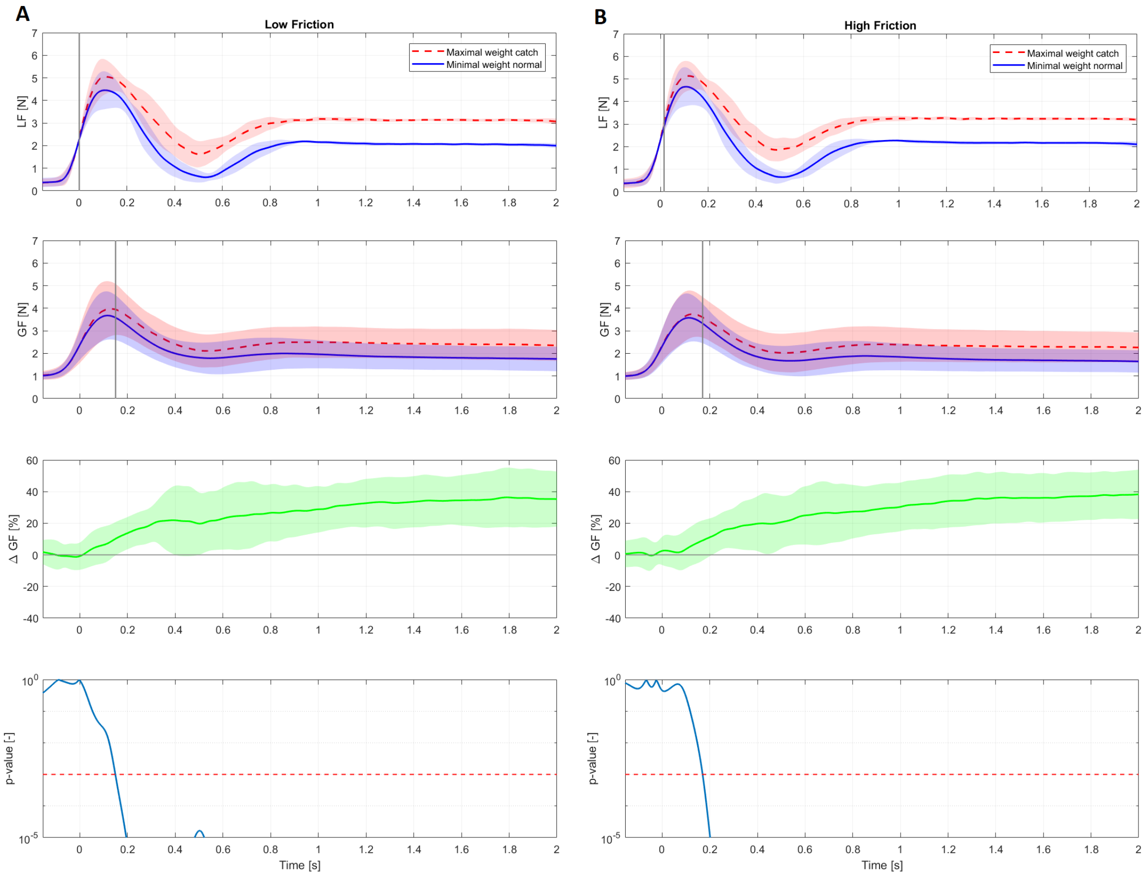

Figure 3.11: *Force adaptation to weight throughout the first movement of maximal weight catch trials. Temporal evolution of the LF, GF, difference in GF and p-value between GF curves during the first movement of A) catch max trials under low friction, B) catch max trials under high friction. The same explanations as for previous similar figures apply.*

Finally, statistical tests affirmed that the LF curves of weight catch trials reached significant difference compared to the LF of preceding trials very early in the movement. In fact, all the p-values drop very early and remain significant for the rest of the trial. The first moments of significance, with respect to the reference time, i.e the first moment a change in weight could be perceived, are the following: at 0s for catch max under low friction, and 15ms after that moment for catch max under high friction. For catch min trials, significance in LF was detected at the reference moment for trials under low friction and 55ms after under the high friction condition. These substantial differences in load force appear at a very early stage of the trials. In fact, a significant change already occurs almost precisely at the first instance of possible feedback about object weight. This is explained by the change in take-off dynamics induced by the modification of the weight. For instance, during a catch max, the LF will continue to increase due to the object not moving while it should have moved if it remained in the same weight condition as before, i.e minimal weight. Although the difference in LF is significant, it is not certain whether this change is perceived by the subjects or not. Nevertheless, this phenomenon could possibly provide a considerable signal giving information about the manipulated object.

In brief, it can not be excluded that the evolution of load force during such a task does not serve as useful information to the brain. Nevertheless, it should also be taken into account that the evolution of the position of the object with time also provides relevant and probably richer information about the weight of the manipulated object.

Once the evolution of the load force during the different types of trials was determined, grip force was subjected to the same analysis procedure.

The results for catch max trials are depicted in Figure 3.11. As could be expected, they indicate that the GF curves of catch trials promptly diverge from the ones of normal trials. However, the significant difference in GF appears somewhat later than for the LF no matter the friction of the glass plates. Indeed, statistical significance is reached after 150ms for catch max under low friction (Figure 3.11A) with a relative difference in GF of 10.10%, and after 170ms under high friction (Figure 3.11B) with a GF difference of 8.24%.

Regarding the evolution of the relative difference in GF, one can observe an inflection point where the GF suddenly increases. This phenomenon happens approximately around the time of the LF peak. This could be an indicator that corrective behavior was triggered shortly before that time, which is in accordance with the previous results regarding the load force. ΔGF then progressively continues to increase until it stabilizes at around 40%, for both types of glass plates.

Figure 3.12 presents the results for catch min trials under low friction (A) and under high friction (B). Altogether, the outcomes are very similar to the ones for catch max trials. Indeed, the moment of significance occurs around the same time, namely 230ms after the reference time for catch min under low friction, and after 140ms for catch min under high friction. The associated differences in GF respectively reach -7.44% and -8.79%. Hence, the same fast adaptation to weight is demonstrated.

As to what concerns the evolution of the relative difference in GF during catch min trials, it shows the same trend, with a downward inflection around the same moment. However, for catch min, ΔGF is smaller overall. This is due to the fact that the real relative change in weight is less important for this type of catch (only 36.67%).

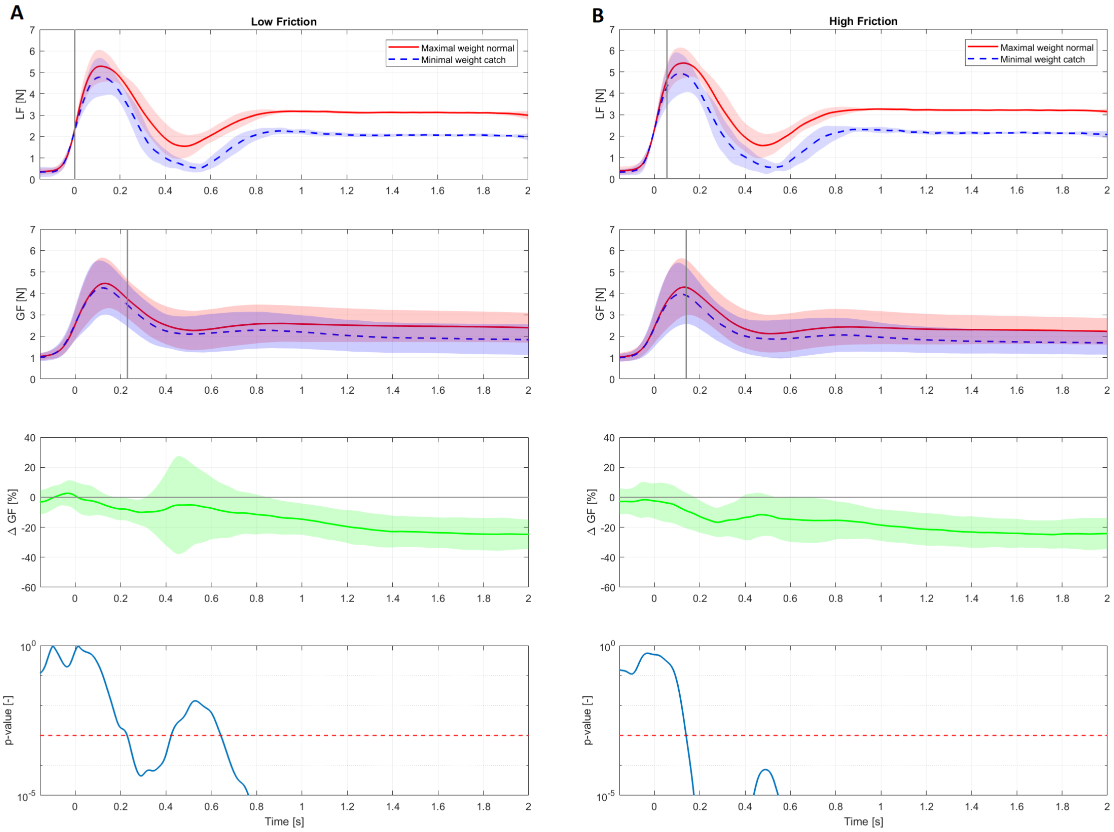

Figure 3.12: *Force adaptation to weight throughout the first movement of minimal weight catch trials. Temporal evolution of the LF, GF, difference in GF and p-value between GF curves during the first movement of A) catch min trials under low friction, B) catch min trials under high friction. The same explanations as for previous similar figures apply.*

Overall, these results for weight catch trials report an important outcome: a significant change in GF systematically seems to arise roughly 150ms after the first moment the subjects could possibly perceive a change in weight. Knowing that the conduction and processing delay of proprioceptive feedback approximates 150ms, this confirms that the central nervous system is able to quickly extract the necessary information about the weight of the object and react to it by adjusting the grip force.[19] Hence, the results suggest that the weight of a manipulated object constitutes a strong and quick signal, that originates from limb position with time and perhaps also from the evolution of the load force.

Finally, since both types of weight catch trials exhibited similar changes in behavior along the trials, relative differences for the different types of catches were compared and are showed in Figure 3.13. It can be seen that the catch conditions show certain symmetry regarding their evolution with time, even if they don't achieve the same magnitude of relative difference in GF. In addition, the plot confirms that a difference in friction does not substantially affect the adaptation behavior.

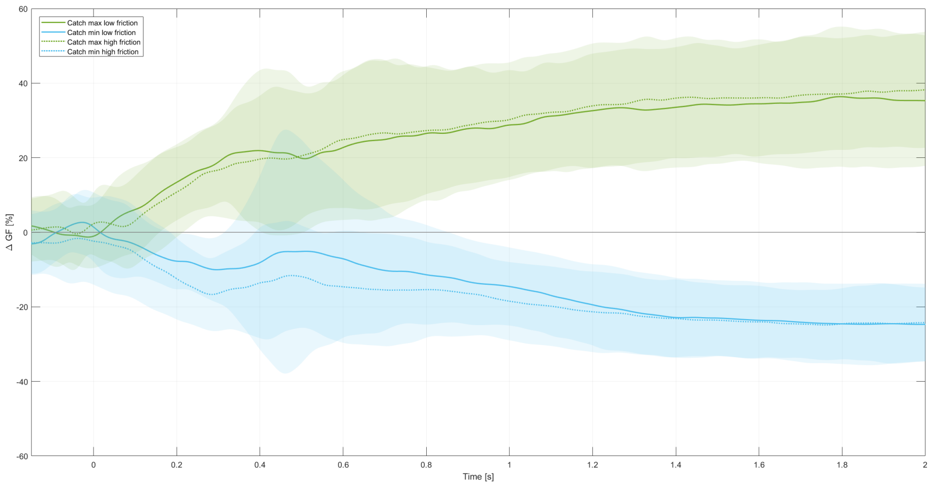

Figure 3.13: *Comparison of the evolution of the relative difference in GF with time across different types of weight catch trials. Green curves depict the mean relative difference for catch max trials under low friction (continuous line) and high friction (dashed line). Blue curves show the mean relative difference for catch min trials under low friction (continuous line) and high friction (dashed line). The shaded areas depicts variance across participants.*

3.5 Finger pad deformations

Now that it has been reviewed what happens at the level of the forces involved during a lifting manipulation task, the question remains about what happens at the level of skin deformations at the surface. Accordingly, analyses of the recorded images were performed to review if there is a correlation between observed gripping behaviors and finger pad deformations.

3.5.1 Evolution during a typical trial

During active manipulation, the fingertip is submitted to a combination of normal and tangential forces, causing skin deformation. As a consequence, compression, stretch or shear strain arise at the level of the skin-object interface, thereby forming strain patterns. Those will be detected by the many mechanoreceptors of the fingertip, providing potential cues to adjust gripping behavior.

Initially, the evolution of strains during the movement was observed for multiple trials across subjects, with the intent of gaining a better idea of how the fingertip is deformed during such a task. The results indicate that reproducible strain patterns take place during a lift-off task, which is in accordance with previous observations for different types of tasks. [5; 13] An example of such deformations during a standard trial is depicted in Figure 3.14. The first line of fingerprints in Figure 3.14B corresponds to horizontal strain rates (in the x direction), the second line corresponds to vertical strain rates (in the y direction) and the third line represents shear strain rates. Note that the direction that is of interest in this study is mainly the strain in the vertical direction since it is aligned with the lift-off movement.

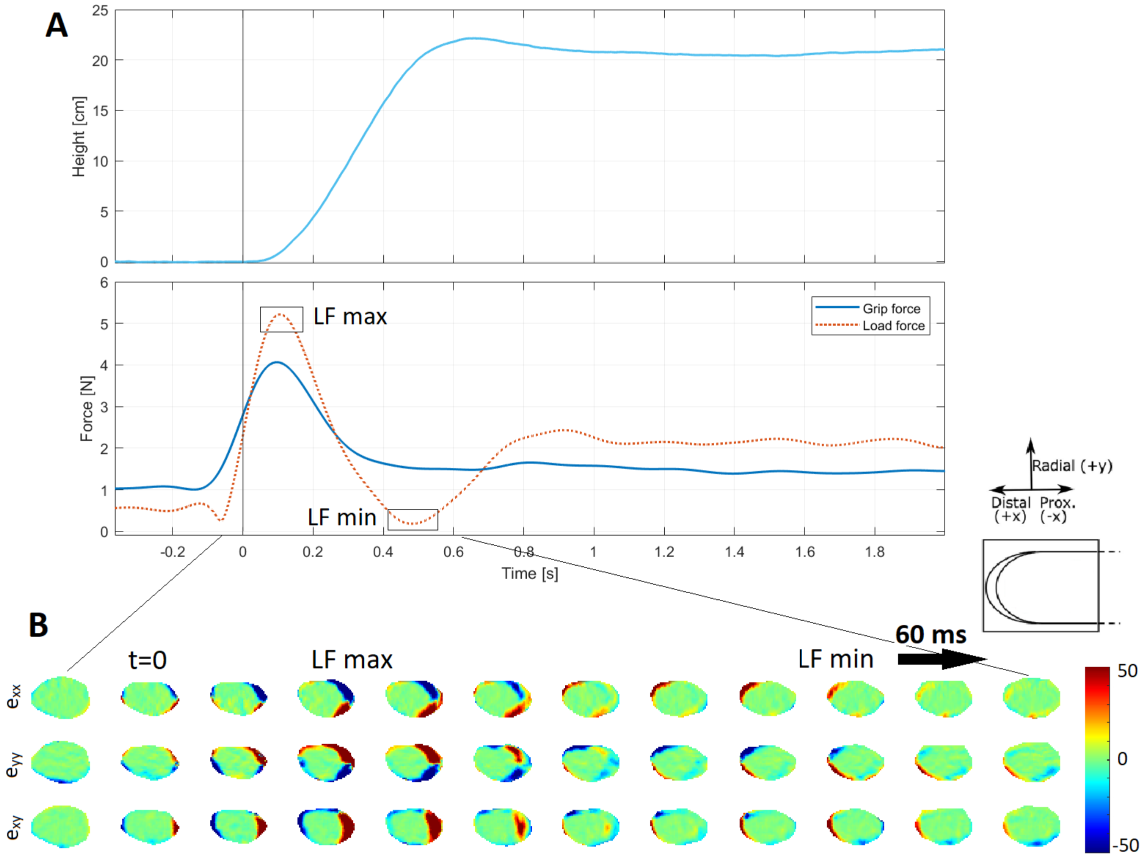

Figure 3.14: *Evolution of strain rate patterns during a standard trial. A) Evolution of position, LF and GF with time for a standard trial of a single subject. B) Evolution of strain rate patterns with time during the lifting movement (time interval depicted in the figure). On the upper right, a small scheme of finger position on the surface and reference system (modified from [8]). The fingerprint strain maps are obtained every 60ms. The first line represents horizontal strain, the middle line represents vertical strain and the last represents shear strain. Negative values (in blue) depict compression and positive values (in red) depict expansion.*

The figure showcases how the strain rates evolve compared to position, grip force and load force. As previously mentioned, the LF curve presents two peaks: a first peak related to the acceleration when the device takes off, and a second negative peak arising from the participants having to slow down the object which has high inertia due to the counterweight.

A first observation is that strain rates evolve in correlation with the LF curve, with greater strain rates emerging at the same time as the LF peaks. Namely, the first LF peak generates the highest amount of strain since the peak is higher than the second one. It is at that moment as well that the strain propagates the furthest in the contact area.

The observed strain pattern follows the same trend as described in several previous studies. That is, strain appearing at the periphery and propagating towards the center. The reason it does not fully propagate to the center is because seemingly, no full slip occurred for this trial. When looking at the vertical strain rates, it can be seen that during the phase leading up to the LF maximum, the upper part of the finger undergoes dilation while the lower part of the finger is compressed. The strains are then reversed when the LF decreases towards the LF minima, with the upper part of the finger being compressed and the lower part being dilated. This reverse in strain pattern results from the inertia of the object which will pull on the skin upwardly when stopping the object. This pattern is consistent with the results of a previous study relating a similar task.[8]

Finally, it can be noted that the horizontal strain rates strongly resemble vertical strains. This results from the elastic properties of the fingertip skin. Hence, the horizontal strains correspond to the opposite of vertical strains, i.e. dilation emerge in the horizontal strain where vertical strains showed compression and vise versa.[13]

3.5.2 Strain rate norm

Since it is difficult to analyze everything that is happening at the level of the skin surface in terms of deformation, strain rate norm (described in Section 2) was chosen as a parameter to evaluate the magnitude of strains occurring at the finger pad surface. Although it does not give an indication about the exact location or direction of deformation, it allows an overall quantification of fingertip deformation.

In order to easily link analyses of strain rate norm to the observed events regarding the involved forces, the same method was used as for the temporal analysis of force curves. Hence, the averaged temporal evolution of skin strain rate norm was computed for the different types of conditions. Besides, the relative difference in surface strain rate norm between conditions was also studied and moments of significant difference were detected by means of statistical tests. Mixed effect models were implemented at each time step (every 0.02s) to derive the corresponding p-value.

As could be expected from the aforementioned results on skin strain patterns, the temporal strain rate norm curves peak around the time of the LF maxima, regardless the type of trial.

Friction catch trials

Figure 3.15 shows the outcomes for catch low trials under maximal object weight (Figure 3.15A) and under minimal object weight (Figure 3.15B). It can be seen that, overall, the evolution of strain norm in the different conditions follows comparable profiles. In fact, this was also observed previously in another experiment involving the effect of friction.[8] The only substantial difference in strain norm arises at its peak for catch low trials under maximal weight. Statistical significance is actually detected at 274ms after the reference time. It can however be argued whether this really constituted sensory feedback to trigger adaptive behavior for two reasons: (1) by looking at the evolution of the p-value, it can be seen that this statistical significance is only reached for a very short period, (2) this moment of significant difference in strains occurs slightly after a significant change in GF has already been detected in Figure 3.7A.

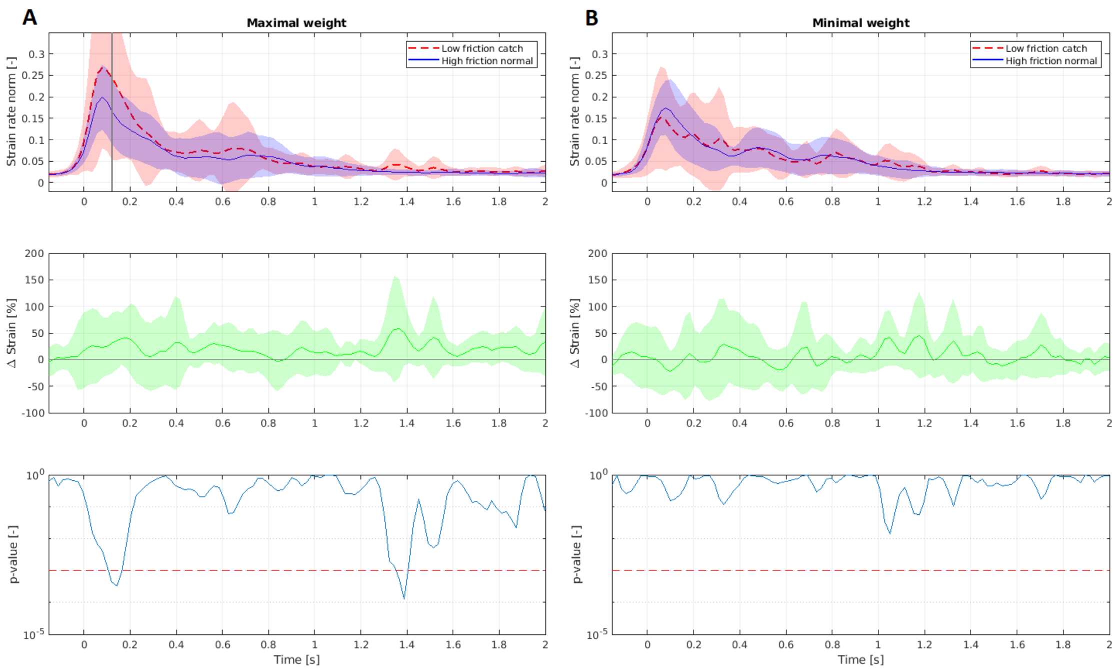

Figure 3.15: *Evolution of strain rate norm with time during the first movement of low friction catch trials A) under maximal weight, B) under minimal weight. The same explanations as for previous similar figures apply.*

As to what concerns catch low trials under minimal weight, it can be seen that no significant difference in strain rate norm was detected. This is in accordance with the results of Figure 3.7B for which, even though the tendency of the GF curves was consistent, no significant difference in GF was detected. It can be seen now that the observed lack of GF adjustment to the change in friction is presumably attributable to the absence of relevant sensory feedback.

Regarding high friction catch trials, for which the results are displayed in Figure

3.16, no relevant significant differences were found. Despite a moment being identified as significant for catch high trials under minimal weight, this result can be excluded due to its lack of relevance. Indeed, this moment appears very late during the trial and is significant only for a very brief instant. In addition, it did not seem to elicit corrective behavior as can be seen in Figure 3.8B. Again, these results, suggesting that no major sensory information about these catches were extracted, are in accordance with the observed absence in force adaptation observed previously (Figure 3.8).

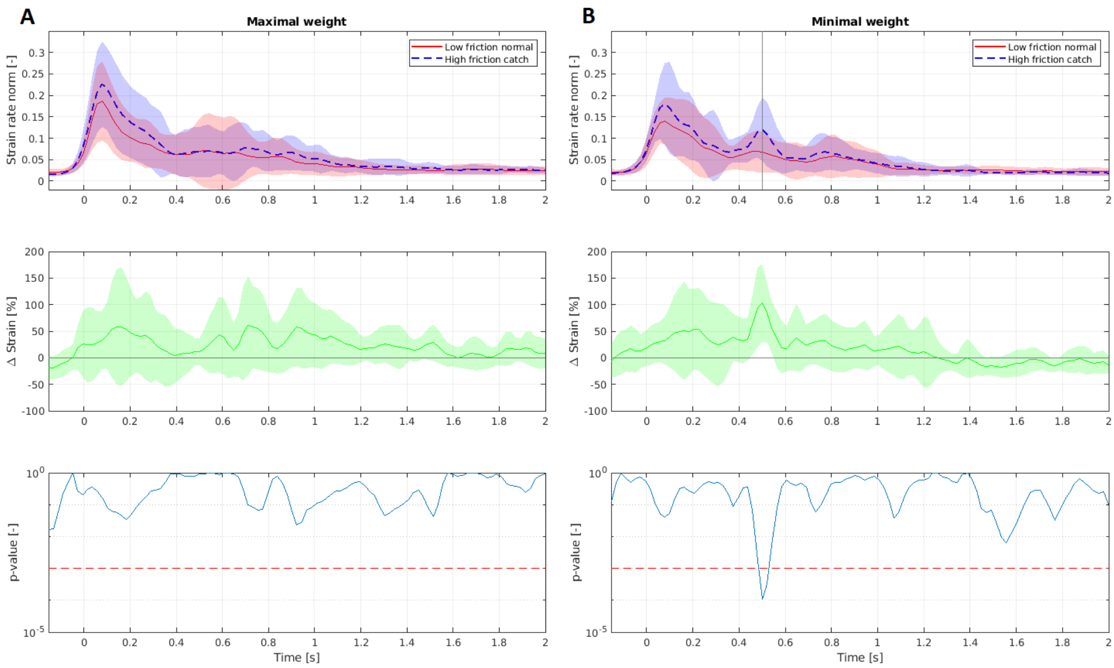

Figure 3.16: *Evolution of strain rate norm with time during the first movement of high friction catch trials A) under maximal weight, B) under minimal weight. The same explanations as for previous similar figures apply.*

More generally, it can be observed that the strain rates are somewhat larger under heavier weight no matter the sign of the change in friction. Indeed, strain rate norm values reach up to approximately 25%/s for friction catch trials under maximal weight, and remain at about 15%/s under minimal weight. This effect might suggest that the security margins, exhibited through the GF/LF ratio, are not the same depending on the weight of the object. Hence, a lower GF/LF ratio leaves more place for deformations to occur, while squeezing harder hinders local deformations of the skin. These results thus imply that subjects seem to keep a higher security margin during the movement under minimal weight. However, this remains an assumption and would have to be further investigated.

Weight catch trials

The results for catch max trials are illustrated in Figure 3.17. As for friction catches, the strain rate norm curves of weight catch trials showcase a similar evolution across conditions, with a peak in strain at the time of the LF peak.

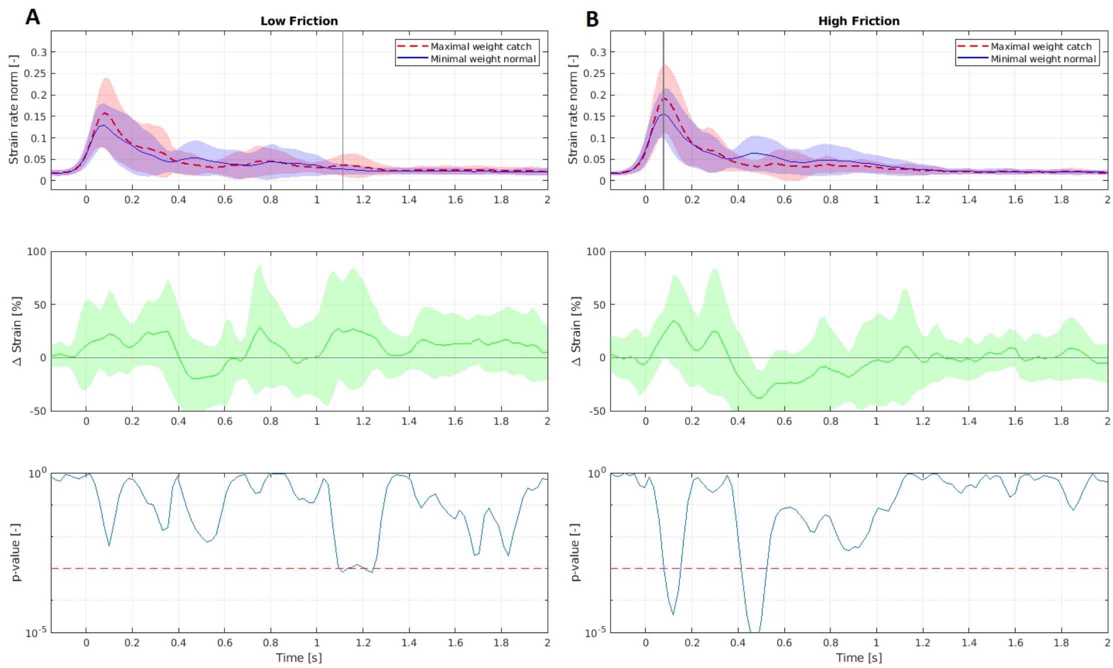

Figure 3.17: *Evolution of strain rate norm with time during the first movement of maximal weight catch trials A) under low friction, B) under high friction. The same explanations as for previous similar figures apply.*

The moment of significant difference in strain rate norm detected for catch max trials under low friction (Figure 3.17A) can be neglected as it results from a very short period of significant p-value. On the other hand, the results of catch max trials under high friction depict a significant difference in strain rate norm 78ms after the reference point. Even though this moment of significance is quite short, it can not be excluded that this provided some sensory information for the brain. Indeed, significant difference in GF was detected for this same catch 170ms after the reference moment (Figure 3.11B). It would thus be possible that this difference in strains at the skin surface provided some feedback contributing to the adaptive response.

Very similar results were obtained for the catch min trials (Figure 3.18, where some brief significant difference in strain rate norm was detected roughly at the same time. Therefore, the same discussion applies: these moments of significant difference in skin deformation could possibly provide cues about a change in weight condition. In fact, previous research on virtual object manipulation revealed that lateral cutaneous feedback contributes to the perception of weight during manipulation.[20]

More generally, the results for catch weight trials support the previous statements about the different magnitude of deformation depending on the weight. Indeed, regardless the direction of weight catch, subjects consistently experienced higher strain rates under maximal object weight.

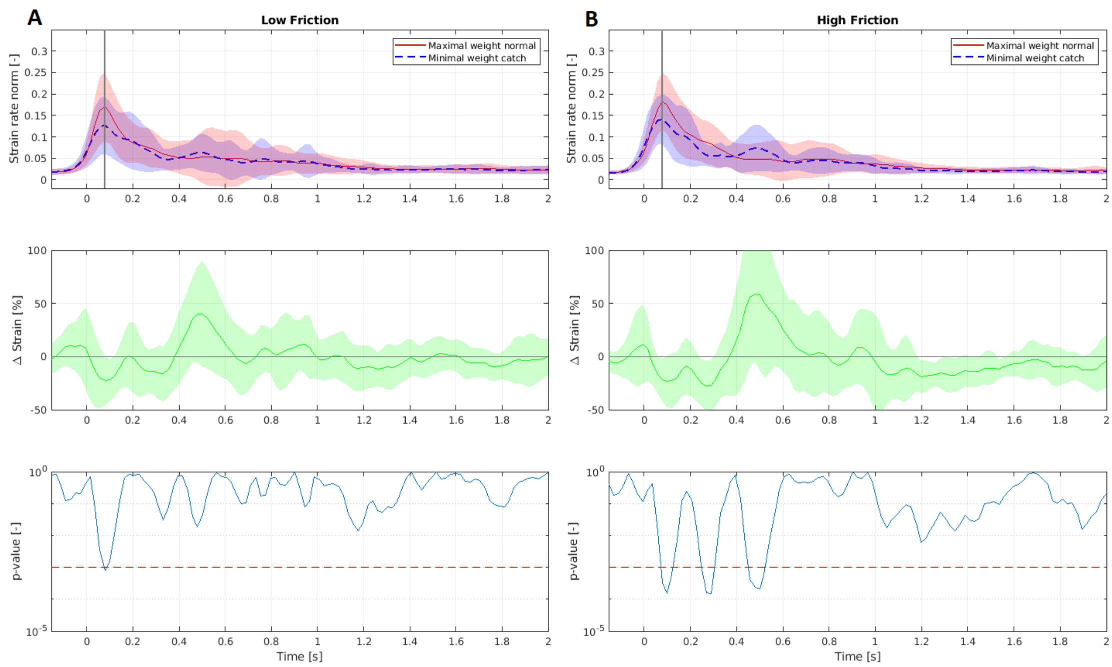

Figure 3.18: *Evolution of strain rate norm with time during the first movement of minimal weight catch trials A) under low friction, B) under high friction. The same explanations as for previous similar figures apply.*

Finally, despite moments of significant difference being detected for some types of weight catch trials, it can be observed that, overall, the subjects were submitted to slightly lower amounts of strain rates during weight catch trials than for friction catch trials. However, the observed difference in gripping behavior was considerably larger for changes in weight.

To understand this, it is important to keep in mind that information about friction only originates from tactile afferents, while feedback about weight can benefit from tactile but also proprioceptive cues such as muscle afferents. Given the adjustment to weight was more pronounced while slightly less strain occured, it implies that the corrective gripping behavior mainly originates from proprioceptive feedback. Moreover, it has been observed that cutaneous and muscle afferents have different latencies, as feedback originating from muscles allegedly seems faster.[3] A hypothesis could thus be that adaptation to weight during active manipulation stems from multisensory integration of both tactile and muscle afferents. Hence, global information about limb position would provide the main feedback, while mechanoreceptors provide secondary information.

To sum up, these results show that important strains take place at the surface of the skin during manipulation. However, these analyses only looked at global strain rate norm evolution, giving no information about direction and location of the emerging strains. Therefore, it would be interesting to evaluate more precisely how the local strains evolve, in order to better understand the obtained results and the observed behaviors.

In addition, the observed highly different levels of variance associated with strain rate norm are in line with the important variability in grip force observed in section 3.4. This phenomenon, already observed in prior research[13], suggests that various levels of grip force were used across participants, leading to substantially different strain amplitudes. Supposedly, subjects would thus manipulate the device with different gripping strategies, consisting in distinct security margins.

3.5.3 Detection of slips

Having observed that the level of deformations taking place during trials widely varies across participants, the manipulation strategy of subjects was investigated more closely. Indeed, they could manipulate the object with different levels of security margin, leaving no or very few slippage occur in the case of high security margin or on the contrary, manipulating with a low security margin allowing slip. To that end, the occurrence of slips was determined under each type of condition (normal, friction catch or weight catch trials) for every subject. The results are depicted in Figure 3.19.

As a reminder, the displacement of the feature points between the first and the last frame were computed. As full slip arises when the central region of the finger, i.e the stuck region, starts slipping, the detection of slip was based on the displacement of those central feature points. Hence, the latter was obtained by taking the first percentile of the computed total displacement of all the features. Accordingly, this corresponds to the points which moved the least between the beginning and the end of the trial. It was considered that slip occurred if the total displacement exceeded 0.1mm. This slip detection procedure was repeated for each trial of each subject.

In order to gain better insight on the factors leading to higher amounts of slip, the results were sorted by condition, and a percentage of slip incidence was determined for each condition. For instance, 50% of detected slip in a certain conditions means that slip was detected for half of the trials under that condition.

Unfortunately, this analysis yields few conclusive results. It can be observed that overall, slips tend to occur more often under low friction and/or maximal weight. However, this is not always the case since several participants experience more slips under some high friction and/or minimal weight conditions. Hence, even though there is some slight tendency for slip to occur more often under low friction and maximal weight conditions, corresponding to more risky conditions in terms of slip, the results are relatively spread and no straightforward conclusion can be made from these results.

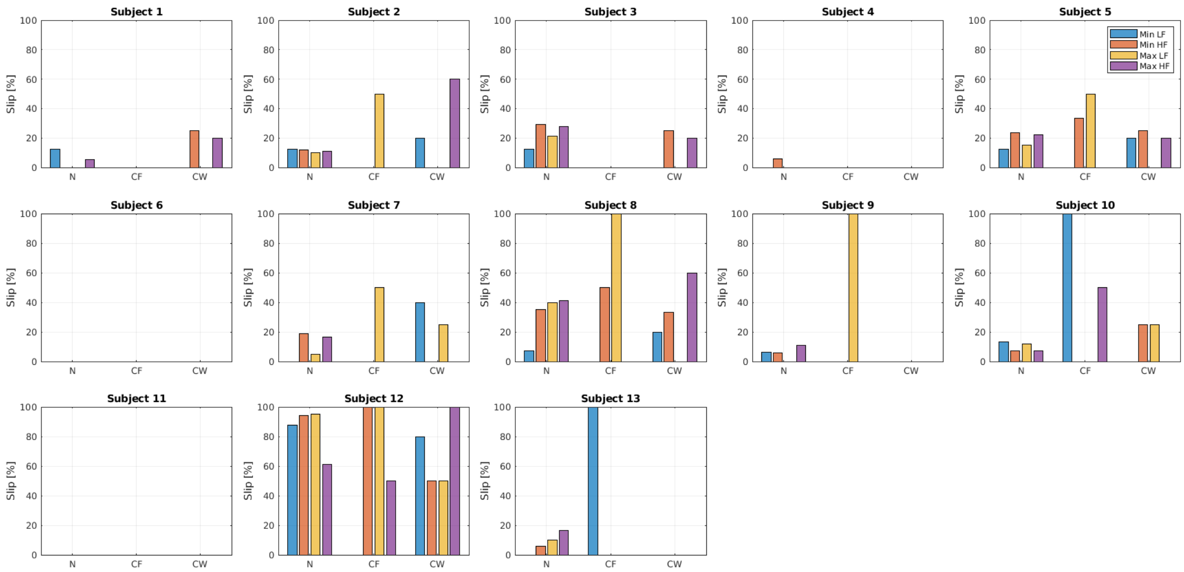

Figure 3.19: *Full slip incidence [%] in each condition across subjects. Each subfigure depicts the results for a different subject. The results are sorted by type of trial: on the left, normal trials (N), in the middle, friction catch trials (CF) and on the right, weight catch trials (CW). For the color bars, blue stands for minimal weight under low friction, orange stands for minimal weight under high friction, yellow stands for maximal weight under low friction and purple stands for maximal weight under high friction. The type of trial indicates what parameter was changed (for example, friction catch in blue is a low friction catch under minimal weight).*

Finally, based on the results, the assumption that subjects used different strategies to manipulate the object seems relevant. Some participants did not allow slips to occur (subjects 6 and 11), while others allowed some slip. Remarkably, subject 12 allowed slip almost 100% of the time. It would be interesting for further analyses to examine the gripping behaviors in terms of applied forces for those different types of manipulation strategies. Moreover, it could be investigated whether these differences in the level of slip occurrence are correlated with the coefficients of friction of the participants.

3.5.4 Finger pad displacement

To improve the understanding behind the results regarding slip, the mean total displacement of the feature points which moved the least, i.e central feature points, was looked into. Figure 3.20 presents the results.

More precisely, as explained in section 2, the first percentile of feature displacement was extracted for every trial of every participant and averaged over identical conditions. This enabled to obtain an idea of the typical fingertip center displacement of subjects in each condition.

Note that the different subfigures do not all have the same scale in order to achieve better visibility of the results.

The outcomes confirm that the level of displacement of center feature points widely varies across participants. Subjects for which no slip was detected previously (subjects 6 and 11) show very limited displacement, at micrometer level. On the other hand, subjects for which a substantial amount of slip was detected, e.g subject 12, shows substantial displacement overall at the scale of millimeters. This supports the assumption that subjects all have their own technique for manipulating objects, resulting in different levels of security margin. As a consequence, the applied grip force, the experienced fingertip deformations and the level of slip will greatly fluctuate across subjects. This has indeed been observed throughout the preceding analysis sections.

Lastly, given the results, it remains difficult to properly correlate displacement and slip to a certain friction or weight parameter.

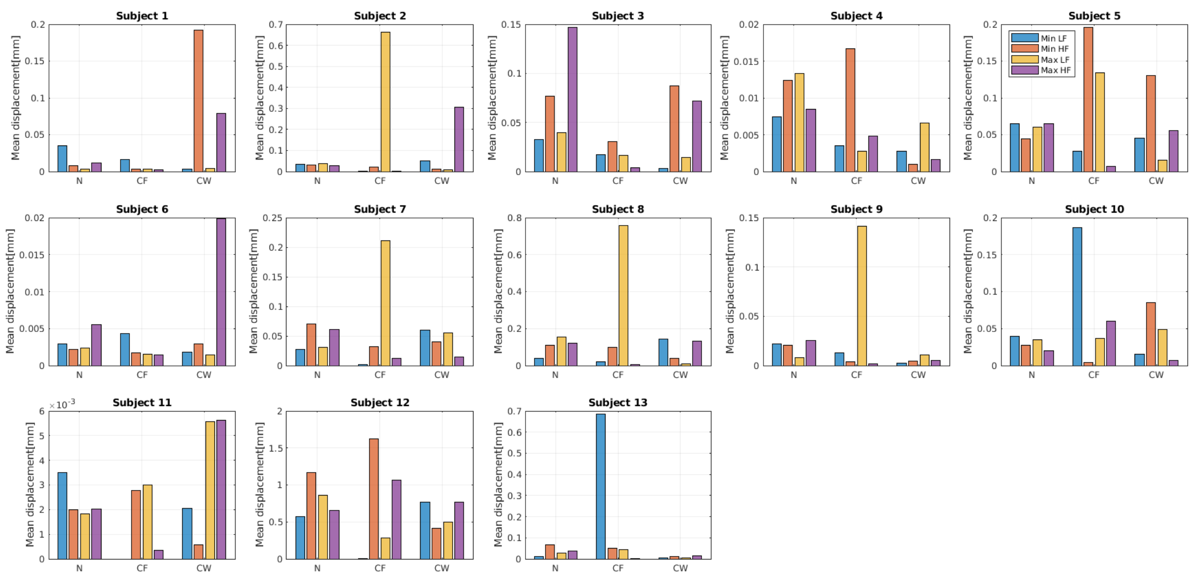

Figure 3.20: *Mean displacement [mm] of the first percentile of feature point displacement inside the contact area between the first and the last frame of each trial. Each subfigure depicts the displacement averaged on trials of a same type for each participant. N = normal trials, CF = friction catch trials, CW = weight catch trials. The color code is the same as in Figure 3.19.*

3.6 Limitations and perspectives

Although this study yielded some meaningful results, several limitations can be identified.

Firstly, the results originate from a manipulation task performed with an object presenting a rigid glass surface. However, humans are exposed to many different types of surfaces throughout everyday activities. Therefore, it would be interesting to perform similar studies with objects presenting different surface properties such as roughness, hydrophilicity or stiffness. In addition, the device only allowed to record images for one finger, in this case the index. It would be interesting to be able to record images for both fingers holding the object, in order to assess whether their behavior during manipulation is similar or not.

A second limitation that has been mentioned previously relies in the construction of the experimental protocol. In fact, the low number of repetitions of friction catch trials caused an issue regarding the reliability of the associated results. The results for friction catch trials were based on only one to three trials per participant. Hence, the results could be submitted to some bias arising from a chance factor or other perturbations. For example, if the participant happened to be less concentrated during that trial, it could induce different behavior and bias the results. Moreover, the same problem arose for double catch trials, i.e trials where both a change in friction and weight occurred, which were insufficient to be submitted to proper analysis. Therefore, it would have been better to only stick to single catch types for this experiment. It would however be interesting to investigate the effect of double catch trials in a future study, in order to examine if there is an additive effect of the impacts of both a change in friction and a change in mass.

Additionally, the experiment being rather long (about two hours), it is very likely that subjects were not equally concentrated throughout the trials. In fact, it has been observed that participants experienced a loss in concentration around the second half of the experiment. This fluctuation in focus may have influenced their behavior during the task.

Another comment can be made about the results for friction. In this study, the values of coefficients of friction for the subjects result from a single measure conducted at the end of the experiment. However, as it has been stated before, friction fluctuates in function of fingertip moisture which presumably varied throughout the course of the experiment. Hence, it would be interesting to be able to associate recorded GF curves with the real measure of coefficient of friction at that moment to see if humans adopt optimal behavior in function of the friction. In fact, a method to determine on-line friction based on moisture and normal force measurements has already been proposed in previous literature.[21] The application of such a method to active manipulation tasks regarding the effect of friction could potentially yield some interesting results.

An additional limitation is due to the fact that friction and weight were always modified during a moment of short break, i.e when the participant was not manipulating the object. Hence, there is a variability factor arising from the fact that the participant may not be performing the task in the exact same way. Therefore, it would be very interesting to be able to change these parameters during the manipulation task itself (an instant change) and evaluate the reaction of subjects in terms of gripping behavior.

Further, the fact that this study only focuses on vertical lifting motions is also a limitation. Indeed, in our daily life, we perform many different types of tasks.

Lastly, it can be mentioned that this study changed the apparent weight of the manipulandum by changing the counterweight at the other end of the system of pulleys. However, this operation has the effect of substantially modifying the inertia of the object. This results in an unusual situation for humans, as we are not used to manipulate light objects with high inertia. Therefore, this study could possibly not entirely reflect the real difference in gripping behavior induced by manipulating objects of different weight.

In brief, this study presented some important limitations to take into consideration when results are interpreted. However, this field of research still has many more questions to answer and many perspectives for future studies are available.

Chapter 4

Conclusion

This study revealed that humans show different adaptation mechanisms to modifications of friction and weight while skillfully manipulating objects.

In terms of the force components at stake during manipulation tasks, this study highlights some events of adaptation to friction, however not always accurate, whereas weight seems to elicit more significant and quick modifications in gripping behavior. Indeed, observed adaptation to friction was only substantial when the new condition generated a high risk of slip, namely for a low friction catch under maximal manipulandum weight. The observed adjustment in grip force however only appeared after about half a second after the sonor cue indicating the beginning of the lift-off, considered to be the earliest moment a change in friction could be perceived by the increase of tangential stress at the skin surface. On the other hand, weight catch trials induced an almost instantaneous modification of the load force, occurring around the earliest moment a change in weight could be discerned. This was then followed by a quick grip force adjustment roughly 150ms later regardless of the sign of the change in weight and the associated risk, implying that weight induces strong and quick feedback for adaptation. In contrast, the results suggest that tactile feedback is less explicit, resulting in a difficulty of consistently adapting correctly to the friction condition.

At a later stage, investigation of the images revealed that lift-off tasks lead to reproducible deformation patterns at the fingertip surface, confirming what had already been observed for other types of tasks. Nevertheless, analyses concerning the evolution of strain rate norms did not yield much concluding observations as the curves followed similar profiles regardless of the type of catch. However, the observed strain magnitudes were in accordance with the reported grip force behaviors, thereby allowing to consolidate previous assumptions behind the adaptation mechanisms to friction and weight. Accordingly, the results confirmed that adaptation to friction relies on tactile afferents, for which it seems that if no difference in signal is depicted, no adjustment in gripping behavior occurs. On the other hand, adjustments of gripping behavior to changes in weight allegedly mainly arise from proprioceptive feedback, while tactile feedback plays a secondary role.

In addition, results confirmed that the manipulation strategies widely varies across participants, suggesting they used different levels of security margins. Hence, this study validates the assumption that dexterous object manipulation differs across people.

To conclude, this study showed that grip force adaptation occurs upon changes of friction and weight, but not with the same accuracy. Further research should still be conducted to clarify the exact operating mechanisms behind the observed behaviors, and to try to gain deeper insight on online corrective grip force adjustment.

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