UCLouvain

**École polytechnique de Louvain**

# The influence of age on fingerpad mechanics during object lifting

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# Abstract

Throughout their life, humans manipulate objects. Reaching, grasping and lifting an object underpins many activities of daily living. However, healthy aging is associated with widespread brain changes as well as a diminished tactile sensibility. A combination of motor and sensory systems is nevertheless required to properly accomplish dexterous manipulations. The present study compared the adaptation to weight and friction changes in 12 elderly and 15 young adult individuals, during a grip-lifting task of a manipulandum by using precision grip. Between trials, the friction and the weight changed unexpectedly. Through force sensors, the forces applied by thumb and index fingers were recorded. Moreover, an optical system enabled to register fingerpad images throughout the experiment. The obtained data allowed to compare the behaviour and the adaptation of each age group to changes. Results suggested that elderly subjects exerted higher forces than young ones, which could partly be due to skin slipperiness. They seemed to faster adapt to friction condition than to weight condition. It also emerged that they adapted less quickly to weight than young subjects. Two different strategies seemed to stand out: young participants tried to minimize the energy spent while elderly ones exerted more force than needed.

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# Chapter 1

# Introduction

## 1.1 General introduction

Picking up a cup of coffee and drinking it, manipulating a pen or holding a plate at a self-service restaurant are tasks that we will perform throughout our lives. They seem relatively easy to accomplish. However, to complete those dexterous manipulations, humans must integrate different sources of information in order to apply an appropriate amount of force. They must also adapt themselves to the surrounding environment. Motor and sensory components are essential for these purposes.

Nevertheless, healthy aging is associated with widespread brain changes, including the sensory and motor systems. Changes in skin properties such as moisturising and elasticity as well as a lower tactile sensibility have also been reported for elderly people [1, 2, 3, 4]. However, during the manipulation of an object, tactile information is crucial. Indeed, when humans come into contact with the object, they are able to perceive different properties such as texture, friction and the relative speed between the object and the fingertip [5]. It is made possible by mechanoreceptors innervating the skin that are stimulated by the deformation of the fingertip. The central nervous system (CNS) is therefore aware of the surface's properties and is able to adapt its motor strategy to the desired task [6]. A lower tactile sensibility due to age may therefore affect the handling of objects. Other elements such as internal models and proprioception also contribute to appropriate handling but these are also subject to change with age [7, 8, 9, 10, 11]. All these modifications can therefore impact the manipulation of objects and lead to a general increase in the applied forces and in the variability of simple movements [12].

The goal of the present work is to evaluate the influence of age on the fingerpad mechanics during object lifting. For this purpose, an experiment was designed with two different age groups: young group - from 18 to 35 - and elderly group - from 55 to 75. The two healthy groups had to perform a grip-lifting task with a manipulandum equipped with force sensors and camera to record images of the index finger. Throughout the experiment, friction and weight were changed unbeknownst to the participants. The adaptation of motor commands to those variations was examined and compared for the two age groups to observe if there were any differences.

Before the presentation of the methods and the results, the state of the art including theoretical concepts involved is presented.

## 1.2 State of the art

### 1.2.1 Force control

Handling tasks play a very important role in our interaction with the environment. The precision grip, involving the tips of the thumb and index fingers, allows us to pick up an object and to move it to perform the desired task. However, the analysis of the forces that are involved during these actions as well as the role of biosensors present on the fingertips are not trivial. Figure 1.2.1 shows the different acting forces during the lifting of an object [13].

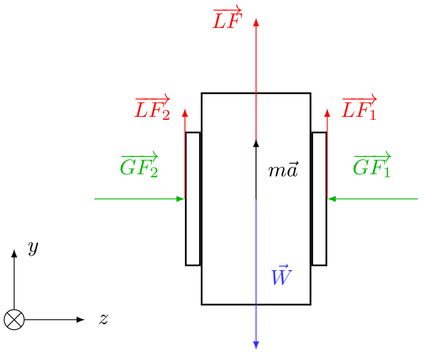

Figure 1.2.1: Forces acting during the lifting of an object. $\overrightarrow{GF}$ represents the grip force, $\overrightarrow{LF}$ represents the load force, $\vec{W}$ is for the weight while $m\vec{a}$ is for the inertial force. Figure inspired by [13].

The *grip force* ($\overrightarrow{GF}$) represents the force applied by the thumb and the index finger normal to the contact surface (in the $\vec{z}$ direction, eq. 1.2.1) while the *load force* ($\overrightarrow{LF}$) is defined as the norm of the sum of the forces applied tangentially to both surfaces by the thumb and index finger (eq. 1.2.2) [14]. The latter is due to the load (eq. 1.2.3). In the case of lifting, the load force is responsible for the upward movement of the object. As soon as the load force is greater than the weight of the object, the latter is set in motion [15, 16].

$$GF(t) = F_z(t) \tag{1.2.1}$$

$$LF(t) = \sqrt{F_x^2(t) + F_y^2(t)} \tag{1.2.2}$$

$$LF(t) = ma(t) + mg \tag{1.2.3}$$

To be sure that the object handled does not slip or fall, one must apply a sufficient amount of force. However, too much force should not be exerted in order not to spend too much energy and not to damage or break the object. During an appropriate handling, there is always a match between the GF and the LF. They automatically change in parallel in order to maintain an approximately constant ratio [15, 17]. This modulation in phase and in amplitude is shown in figure 1.2.2.

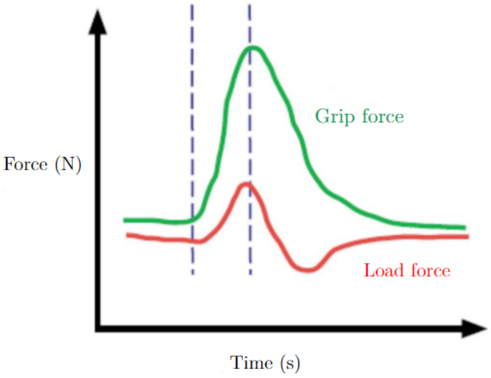

Figure 1.2.2: Coupling LF-GF over time. Modified figure from [13].

Normally, this ratio is set to fit the anticipated frictional condition. Then, it is updated thanks to tactile afferent information [15]. However, according to a study conducted by K.J. Cole [12], elderly persons exercise more GF than necessary to prevent slip. Indeed, this study aimed to evaluate the grasp force control in older adults and it emerged that elderly persons employed grip forces that were, on average, twice as large as those of the young participants. Some produced forces many times greater. Grip forces were also significantly more variable across trials in elderly subjects. Then, the questions are *"Which elements help us to adjust our grip force?"* and *"How can age have an influence on this complex phenomenon?"*.

Firstly, **visual inputs** provide key information about the size, the shape and the distribution of weight of the object to be manipulated. Those afferents allow us to refine our priors about an upcoming action and influence the fingertip forces during the object's manipulation [18]. These visual cues are also useful to assess any changes in the surrounding environment, especially in case of obstacles or disturbances. Visual function inevitably deteriorates with age because of numerous anatomic changes occuring in the eyeball. These reduce the quality of sensory inputs to visual processing [19, 20].

Secondly, the **proprioception** plays an important role too. It can be defined as *"the normal awareness of one's posture, movement, balance, and location based on the sensations received by the proprioceptors"* [21]. Then, proprioceptive information coming from muscles, tendons and ligaments allows the brain to estimate the position and the movements of the different parts of the body as well as the force that they exert. It also allows to maintain the body balance [13, 22]. Moreover, it plays an important role in the planning of precise and coordinated movements [7]. Proprioception deterioration with aging is traditionally viewed as evidence, due to physiological changes. Then, it can partially lead to a decline of motor coordination and balance [7, 8]. However, it is important to note that in a recent study from KULeuven [23], proprioception appeared unimpaired for elderly participants.

Thirdly, **tactile inputs** are sent to the central nervous system (CNS) by mechanoreceptors that innervate the skin and that are stimulated by skin deformation. The latter can be due to partial slips for example. The CNS is then able to adapt the motor strategy since it is aware of the properties of the surface which is in contact with the skin [6]. Without a tactile feedback, the internal models can not be updated for the current task [17]. In primates, the hands, together with lips, are the body parts that contain the greatest number of mechanoreceptors [22]. Section 1.2.5 resumes the influence of age on skin properties and therefore on tactile inputs.

Finally, **internal models** are necessary [13] :

- to calculate the future inertial forces resulting from the displacement of the manipulated object.
- to combine the gravitational and inertial forces giving rise to the overall load force which must be compensated by the grip force.
- to estimate the future trajectory on the basis of the instructions sent to the member.

The correct adaptation to various situations confirms the successful adjustment provided by internal models [13]. The synchronization shown in figure 1.2.2 proves that there is an anticipation. If there were only tactile and visual feedback, there would be a delay of the grip force compared to the load force. This mechanism is explained in the section below, as well as the evolution of this function with age.

### Internal models

An internal model is a system which mimics the behaviour of a natural process [24]. The figure 1.2.3 is based on a scheme found in the journal *Current Opinion in Neurobiology* [25]. One can observe that there are one input - the desired arm trajectory - and three outputs - the movements of the hand, the arm and object.

There are several steps:

1. Based on the desired trajectory, the inverse model calculates the command to be sent to the arm. The inverse model is therefore a controller as it provides the necessary motor command to achieve the desired state transition [13, 24].
2. The input of the forward model is the efference copy of the motor command. This model reproduces the behaviour of the arm and from this, calculates the trajectory. Then, it can be considered as a predictor [13, 23, 24].
3. On the basis of the mass and the acceleration as well as all the contextual information, the grip force controller determines the appropriate grip force [13, 24].

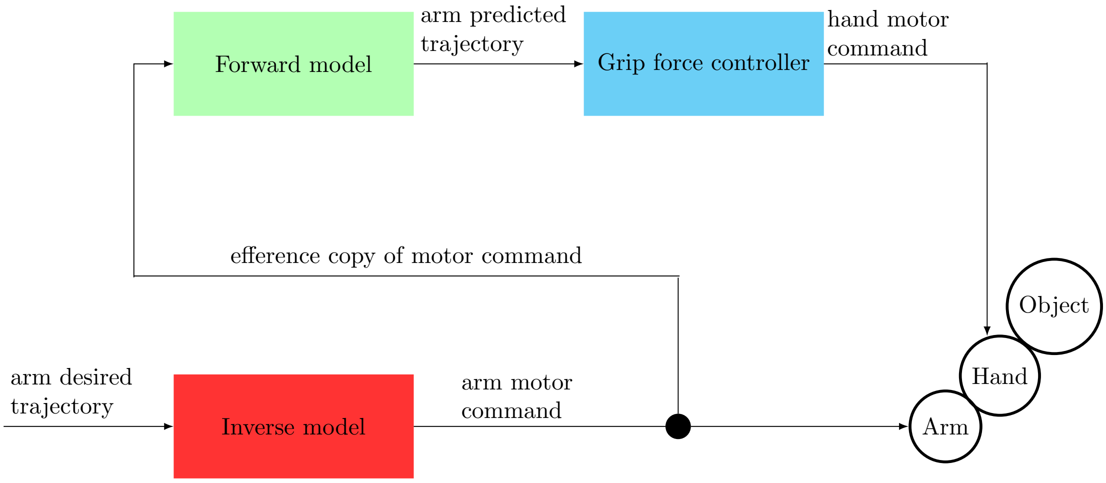

Figure 1.2.3: Internal models: Firstly, the inverse model calculates the command to be sent to the arm. Secondly, the forward model calculates the trajectory of the hand/arm on the basis of the efference copy of the motor command. The grip force controller determines the appropriate grip force. Figure inspired by [25].

Forward and inverse models must be adaptable and updated. Indeed, both depend on the dynamics of the motor system, which change according to the contextual conditions and throughout life. If the updating does not occur properly, there will be a discrepancy between what we believe we can do and what we can really do [26]. The feedback control based on sensory signals allows an adjustment in motor commands. However, as there is a sensory delay (e.g. 100 ms for vision [27]), it is necessary to anticipate [24]. Nevertheless, if a disturbance occurs, the only way to appropriately react is through sensory feedback [24].

According to K. Vandevoorde and JJ. Orban de Xivry [9], internal model function is not affected by age, even if the aging brain is slower to adapt to external perturbations. They suggest that age-related decline in motor adaptation is mainly due to cognitive deficits. Another study from R. Moran et al. [11] suggests that a greater precision is afforded to predictive signal with aging due to the accumulation of experience throughout life. These two studies and others [10, 23] point the fact that older adults rely more on internal model function than on sensory feedback. It can be explained by the fact that the sensory sensitivity is reduced with normal aging (reduced precision). Therefore, according to the principles of Bayesian integration (i.e. signals combined in function of their reliability or precision), a lower precision of sensory signals would lead to a higher reliance on predictions. Similarly, a greater accuracy of predictions from internal model with aging would also lead to an increase of the weight of predictions. [9, 10, 11, 23]

### 1.2.2 Factors influencing the required amount of grip force

Four important factors influence the grip force level that is applied [28]:

- The *mass* of the object.
- The *gravity* and the *acceleration*.
- The *friction* between the object and the skin.
- The *safety margin* set by the subject based on prior experience.

#### ***Mass***

The mass of the object is present in the two components of the load force: the weight and the inertial force. The inertia can be defined as *"the tendency of a body to keep moving once it is set in motion"* [29]. It can also be understood as the resistance opposed to the acceleration of an object, which is proportional to its mass. For example, the heavier the object, the greater the force required to set it in motion.

#### ***Gravity and acceleration***

From birth on Earth, our brain copes with gravity. It is able then to anticipate its effects [30]. The gravitational force that the earth exerts on a body is called the weight of this body [31]. During the lifting of an object, gravity slows it down since it has a downward direction. However, when lowering an object, gravity and acceleration are in the same direction. At rest, the acceleration is equal to zero. In this case, only the weight of the object has to be counteracted ($LF = mg$).

### ***Friction force***

The friction force can be defined as *"a resistance encountered when one body moves relative to another body with which it is in contact"* [33]. This force acts parallel to the surface, in the direction that opposes sliding [31]. The equation 1.2.4 shows that the magnitude of the friction force $f$ is approximately proportional to the magnitude of the normal force $n$. The parameter $\mu$ is called the friction coefficient. The more slippery the surface, the smaller this coefficient [32]. A representation of the forces involved when one body moves relative to another body is shown in figure 1.2.4.

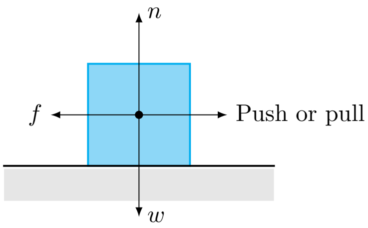

Figure 1.2.4: Forces involved when a block is pushed or pulled over a surface. $n$ represents the normal force, $w$ is the weight of the object and $f$ represents the friction force. Figure inspired from [32].

$$f = \mu \cdot n \text{ (N)} \tag{1.2.4}$$

During the manipulation of an object, the static coefficient of friction $\mu_{static}$ between the fingers and the object must be assessed. Indeed, a sticky surface is squeezed less firmly than a slippery surface [34]. However, the static friction coefficient varies nonlinearly with the normal force applied and increases at low normal force levels [35]. Moreover, it depends on the gender and the age of the subject (see subsection 1.2.5), on the orientation angle of the finger and on the type of movement [36]. It is also influenced by the experimental conditions as well as the skin moisture. For example, if the subject is stressed, the degree of humidity will be higher and the friction coefficient will be different [13]. Indeed, a moist skin provides a larger effective contact area since the moisturizing decreases the rigidity. This results in an increase of the net friction (until a certain point) [6, 36]. However, the relationship between moisture and the friction coefficient is non-linear (bell shape) [13, 37].

In order to avoid letting the object slip, the GF/LF ratio must be greater than the inverse of the friction coefficient $\mu$ (eq.1.2.5) [13] :

$$\frac{||\overrightarrow{GF}||}{||\overrightarrow{LF}||} \geq \frac{1}{\mu} \tag{1.2.5}$$

In a study by F.Schiltz et al. [14], it was demonstrated that young subjects adjusted their GF to a change in friction during a lift-off movement within 370 ms after contact with the surface. The relative difference in GF was of the same order of magnitude as the relative friction difference. It is important to underline that there was an asymmetry of the participants' behaviour between the transition high friction to low friction level and the reverse transition. It took less time to reach an adapted level of GF when the subject passed from high friction to low friction. This seemed logical. Indeed, if the adaptation was too slow, the object should logically have fallen since the surface was more slippery. Concerning the deformation of the fingerpad, when the friction was lower, deformations advanced faster and deeper into the contact area. On the basis of those two observations, the authors suggested that local and partial deformation patterns are used by the nervous system to adjust the GF as a function of the frictional condition. Participants did not notice that different materials were used. However, they all adapted their GF. To my knowledge, the deformation of fingerprints of elderly people during object lifting has not yet been studied. However, a decrease in $\mu_s$ in elderly people has been reported by K.J Cole [12].

***Safety margin***

Previous work has suggested that to reduce the risk of slip, grip force control includes a safety margin [12, 38]. It means that the actual GF/LF ratio is consistently higher than the minimum GF/LF ratio avoiding slips (slip ratio) [38]. Moreover, Andre et al. [6] observed that for equivalent contact states, the safety margin increased with skin hydratation. According to a study of grasp force control by K.J. Cole [12], the GF that elderly subjects produced was larger than would have been predicted from their skin slipperiness. They suggested that this phenomenon could represent a strategic response due to tactile sensibility impairment. Indeed, it allows to reduce the reliance on hand afferent signals.

### 1.2.3 The skin

With a surface of about 2 $m^2$, the skin is the largest organ of the human body. It is a continuous system which performs diverse functions. As well as being a physical barrier, it also has sensory and immune properties [39]. There are two types of skin in humans :

- **Glabrous skin** : this hair free skin is found mainly on palms of the hands and soles of the feet. It is innervated by specialized nerves that allow us to understand subtle tactile details [39, 40]. The sensory receptors as well as sweat glands are numerous. [40]
- **Hairy skin** : more than 90% of the body is covered with this type of skin. Sensory receptors are more sparse than in glabrous skin.

In this work, the glabrous skin is the one of interest. Figure 1.2.5 shows the three layers (epidermis, dermis and hypodermis) as well as the four classes of cutanueous afferents present in this type of skin. The latter innervate different types of mechanoreceptors which are Meissner's corpuscles, Pacinian corpuscles, Merkel's discs and Ruffini's corpuscles. The cutanueous afferents can be of type 1 or 2, according to the size of the receptive field. Mechanoreceptors innervated by type I afferents are found close to the surface and have a small and defined receptive field. Those innervated by type II afferents are localized deeper in the skin and have large receptive field, less defined [22].

The epidermis of the glabrous skin is characterized by the presence of ridges and furrows that form the fingerprints. This complex geometry is therefore likely to have an impact on friction [14]. The ridges determine the effective contact area within a contact area. However, when gripping a material, geometry and mechanics of skin change because of humidity. Indeed, sweat pores are present at the surface of the skin and produce humidity at the interface [14, 36].

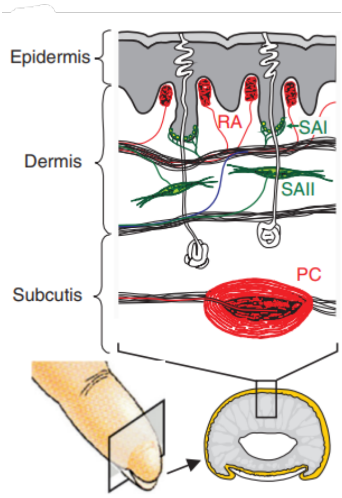

Figure 1.2.5: The three layers and the four cutaneous afferents of the glabrous skin. Slowly adaptating type 1 (SA1) and 2 (SA2) afferents respectively innervate Merkel's discs and Ruffini's corpuscles, the rapidly adaptating type 1 (RA1) and 2 (RA2 or PC) respectively innervate Meissner's corpuscles and Pacini corpuscles. Figure taken from [22].

### Influence of age on skin properties

Several studies have illustrated the effects of age on skin properties and on tactile perception:

- The sweat production by sweat glands from the glabrous skin decreases [12].
- The sebum content present on the skin surface declines in an age-dependent manner [1].
- The contact area clearly reduces with age for both men and women [4]. Indeed, the hydratation of the stratum corneum (i.e. the outermost layer of the epidermis) decreases in aged skin [1].
- Both accelerated degradation and decreased syntheses of collagen and elastin leads to reduced cutaneous elasticity in aged people [1].
- Due to menopause, the women's skin changes. Indeed, estrogen loss at this period results in atrophic skin changes and acceleration of skin aging [2, 3]. Estrogen deficiency following menopause leads to a thinner and dryer skin with less collagen and less elasticity [3].
- The size, the density, and the complexity of some mechanoreceptors - Meissner and Merkel corpuscles - decline significantly with aging [41, 42]. Meissner corpuscles are normally sensitive to dynamic skin deformation at intermediate frequencies (5-50 Hz) while Merkel corpuscles are sensitive to slow skin deformations [22]. It leads to a diminished tactile sensibility [12].
- Vibrotactile detection thresholds and minimum detectable levels of vibration increase [4].

All these age-related elements could therefore have an impact on the handling of objects as they are involved in the sensitivity as well as in the friction coefficient between the skin and the manipulated object.

### Fingerpad deformation

As mentioned in the section 1.2.1, tactile inputs play an important role in the adaptation of the grip force by the CNS. This is due to tactile afferents innervating the hand and the fingers which encode the deformations and the vibrations produced in the skin during object manipulation. Morevover, the tactile afferents feedback is very important to properly react to unexpected variations in object load or surface friction [43].

André et al..[6] showed that there are systematically partial slips at the periphery of the contact zone (fingertip - object) during tangential loading of the fingerpad. This phenomenon is illustrated in figure 1.2.6.

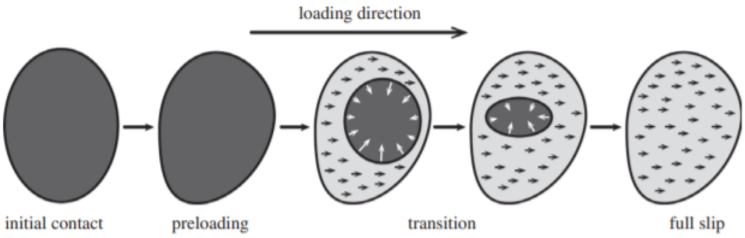

Figure 1.2.6: Evolution of the dynamics of finger contact from the initial contact to full slip. From left to right: initial contact, preloading phase, slip onset starting at the periphery, growth of the slip region, full slip. Partial slips start at the periphery of the contact area, aligned to the loading direction. Then, it progresses towards the center of the contact area until reaching the point of a full slip. Figure taken from [6].

First, when the fingertip makes contact with the object, an elliptical contact region is formed. Between the initial contact and the preloading phase, there is a reduction of the contact area because of the initial deformation of tissues [6]. At the beginning of the loading, partial slips start at the periphery of the contact area, aligned to the loading direction. After, it progresses towards the center of the contact area until reaching the point of a full slip [43]. Then, the slip is neither instantaneous nor homogeneous. Indeed, there are slipping and non-slipping areas and the deformation values are the greatest at the periphery [44]. It was also shown that the contact area linearly decreases when the tangential force increases, until it reaches 0, which corresponds to the total slip [6][43].

During the transition phase, the contact dynamics may inform the central nervous system to correct the behaviour in order to maintain grip stability [6]. However, the deformation dynamics depend on the skin hydration. Moist skin is more flexible than dry skin. Therefore, the bulk dynamics of deformation are slower with moist skin and it is easier for the CNS to sense them and correct the action [6]. In addition, the hydrophilic or hydrophobic nature of the surface also plays a role. Indeed, Allan Barrea et al. [5] showed that slip detection is impeded when the plate is coated with a hydrophobic surface. The latter dramatically decreases the contact friction and therefore the amount of fingertip deformation. Yet, in order to be detected by the subjects, the deformation must be sufficient.

Especially for the lifting of an object, F.Schiltz et al. [34] showed that during the acceleration phase, the bottom part of the fingertip was compressed while the top part was dilated. During the deceleration phase, it was the contrary.

## 1.3 Goals

The main goal of the present work is to evaluate the influence of age on the fingerpad mechanics during object lifting. For this purpose, participants - divided into two age groups (18-35 and 55-75) - had to perform a lifting movement followed by a static phase with a manipulandum. The latter was equipped with a camera and forces sensors. Therefore, forces applied by the participants and images of the index finger were recorded. During the experiment, changes in friction and weight occured, unbeknownst to the participants. The collected data allowed to evaluate and compare the adaptation of motor commands to variations of the two age groups.

First, we will be interested in the behaviour of the two groups during the normal trials. We will look at whether the kinematics of the movement were the same for both age groups and at the range of grip force applied. Second, we will observe if the two age groups behave in the same way depending on the conditions. Is a higher grip force used for riskier conditions? If so, what is the difference in GF between the two conditions? Third, we will observe the behaviour during the static phase of catch trials to see if there was an adaptation. Fourth, if there is an adaptation, we will evaluate the time at which the change in GF behaviour occurs. Is the time frame more or less equal between the two age groups ? Finally, we will look at the strain rate norm to evaluate if fingerpad strain gave information about the level of GF to apply. We will also compare this strain rate norm across the two age groups. The same procedure will be applied for both adaptations (friction and weight).

This comparison is important to evaluate the influence of age on object manipulation. Indeed, healthy aging is associated with widespread brain changes, including the sensory and motor systems. Moreover, modifications in skin properties have also been reported for elderly people. By comparing the adaptation to friction and weight between the two age groups during a grip-lifting task, we could evaluate a part of the influence of sensory and motor alterations due to age.

# Chapter 2

# Methods

## 2.1 Participants

Twenty-eight healthy volunteers participated in this experiment. They were separated into two age groups as shown in table 2.1.

| | **Subjects aged 18 to 35** | **Subjects aged 55 to 75** |
|---|---|---|
| Men | 11 | 6 |
| Women | 4 | 7 |
| **Total** | 15 | 13 |

Table 2.1: Description of the subjects who participated in the experiment.

There were four inclusion criteria :

- being within these two age ranges (18-35 or 55-75).
- being right-handed or ambidextrous.
- not suffering from any neurological or motor disorder.
- not having the skin of the thumb/index finger of the right hand damaged.

Each of these subjects provided written and informed consent to the procedures and the study was approved by the ethics committee at the host institution (UCLouvain, Belgium).

## 2.2 Apparatus

To determine the different forces applied and to characterize the fingerpad deformation during active manipulation in real time, a manipulandum equipped with forces sensors and a camera was used. The device called *Active Touch* had a real mass of 540 g. At rest, it was placed on a table with a hole for the cables to pass through. In the experiment, a counterweight attached with a system of ropes and pulleys partially compensated the weight. In order to evaluate the impact of a weight change on the forces and skin's deformation, a mass of 110 g was added or removed once a block on the counterweight to modify the weight of the manipulandum. Then, the counterweight had a mass of 210 g or 320 g. This led to a manipulandum apparent weight of $\sim$3.1 or $\sim$2 N respectively.

The main parts of the manipulandum are the following:

1. **Accelerometer** : sensitive to acceleration.
2. **Force and torque sensors** : one at each side of the manipulandum, they measure the forces exerted by the index finger and the thumb. From those measurements, GF and LF can be extracted.
3. **Lighting** : illuminates the glass on which the index finger is located.
4. **Half mirror** : allows the reflection on the camera.
5. **Glass plates** : correspond to the contact area with the fingers. The force applied on those glasses is measured by the force sensors and the image of the index finger can be obtained. Those plates are removable. They can be interchanged to vary the friction. A checkerboard pattern is glued on the glass that is imaged to measure the relative motion between the plate and the camera. It also allows to check the focus of the camera. This can be seen in figure 2.2.2B.
6. **High resolution camera**: collects the light coming from the glass. Images of the index fingertip skin are recorded at 100 frames per second.

A scheme of the manipulandum with the corresponding numbers and a picture of the manipulandum are shown in figure 2.2.1. In this experiment, the humidity sensor was not used.

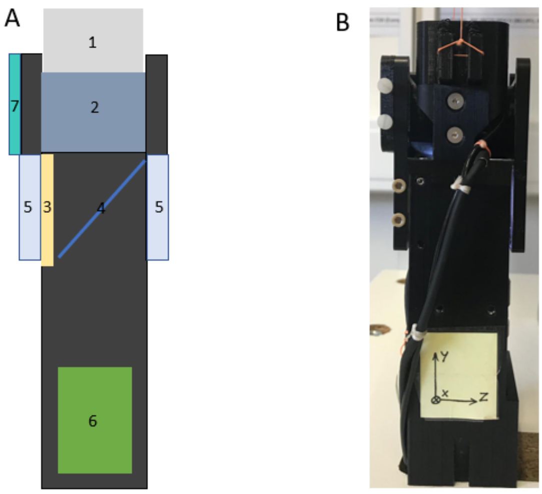

Figure 2.2.1: **A:** Scheme of the manipulandum (1) Accelerometer (2) Force sensors (3) Lighting (4) Half mirror (5) Glass plates (6) Camera (7) Humidity sensor. **B:** Caption of the manipulandum *Active Touch.*

Moreover, an optical distance sensor was used to measure the position of the counterweight and consequently, the one of the manipulandum. The position, forces, torques and acceleration were acquired at 200 Hz.

### 2.2.1 Optical system

The optical system allowed to image the fingertip-plate contact. Figure 2.2.2A shows the different parts of the optical system in more details. A part of the light was reflected on the half mirror and the rest was transmitted through the mirror to illuminate the finger. Again, on the glass in contact with the finger, part of the light was reflected and the other part was transmitted. As a result, the darker areas corresponded to contact zones while the light areas corresponded to the non-contact zones. Sometimes, white dots were visible. They corresponded to the pores of the skin. The light being emitted from the side where the thumb is, it was only possible to monitor the index finger. A typical image obtained with this optical system is shown in figure 2.2.2B.

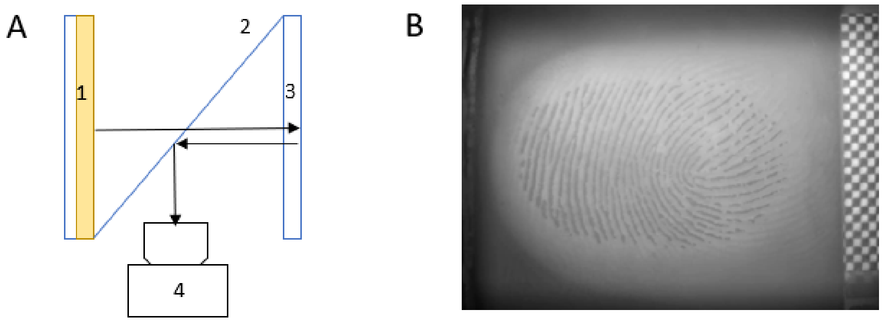

Figure 2.2.2: **A:** Optical system. (1) Light source (2) Half-mirror (placed at a 45° angle (3) Glass where the index is placed (4) Camera. **B:** Typical image of a finger pad obtained with the optical system. A checkboard pattern is glued to the right of the plate to measure the relative motion between the plate and the camera. It also allows to check the focus of the camera.

### 2.2.2 Glasses

For this experiment, two sets of glass plates with different levels of friction were used. The high friction glasses were transparent flat plates while the other set had nanoscale patterns on its surface. Therefore, the real contact area between the fingers and the plates was smaller, leading to a lower friction coefficient.

## 2.3 Experimental procedure

After the consent form reading, participants were asked to wash their hands, with water and soap, to remove impurities. The hands dried in the open air during the explanation of the experiment by the experimenters. The latter also carried out a demonstration trial. It consisted in a lifting movement of the manipulandum followed by a static phase at a height of about 20 cm. The object had to be held in precision grip (i.e. with the thumb and the index fingers) with the right hand as it is shown in figure 2.3.1. Subjects were only instructed to pay attention to the positioning of the manipulandum in space, to the timing and minimum force application. Then, subjects stood facing the table where the manipulandum was located. They could become familiar with the set-up, learn to place their index finger correctly on the glass and perform the movement before the start of the recordings. As soon as they were ready, the experiment began. Throughout the trials, the subjects were guided by audio signals:

1. The first sound indicated that the subjets could grip the manipulandum. The volunteers had 10 seconds to place their fingers in the center of the glasses and to calibrate their grip force to 1 N. They were guided by the experimenters in those tasks and they could also see the image and the applied force on the computer to help.
2. After 10 seconds, a second auditory cue indicated that the subjects had to lift the device to a height of about 20 cm. To evaluate this height, the volunteers were helped by visual cues as shown in figure 2.3.1.
3. A third sound, 0.8 seconds later, warned that the fingers should be at the level of the visual indicators. The participants were then asked to maintain the object at this height for 1.5 seconds.
4. After 1.5 seconds, another auditory cue indicated that the subject had to put the manipulandum down. The time granted for this movement was also 0.8 seconds but they could slow down to gently put the device on the table.
5. A last sound instructed the subjects to remove their fingers from the manipulandum.

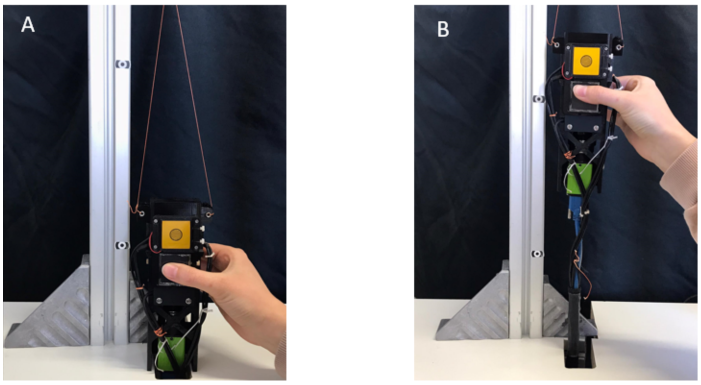

Figure 2.3.1: **A:** Subjects had 10 seconds to place their fingers correctly on the glass for the fingerprint to be centered in the camera's field of view. They also had to calibrate their force to 1 N. **B:** Subjects had 0.8 seconds to lift the manipulandum up to 20 cm high. The fingers should be at the level of the visual cues. They had to hold this position during 1.5 seconds before placing the manipulandum back on the table. Throughout the trial, the object was held in precision grip (i.e. with the thumb and index fingers).

The experiment contained twenty blocks of six trials each. The first two blocks were considered as training blocks and were excluded from the data analysis. After each experimental block, the subjects were asked to sit on a chair in a location where they could not see the manipulandum and the experimenters. During this time, the experimenters interchanged the glasses in order to vary the friction if necessary (Fig 2.3.3), without the participant noticing it. Even if the glasses were not changed, the procedure and the pause time (two minutes) were the same to avoid raising suspicions. The first trial of a block with a different friction was called "friction catch trial". At the beginning of each block, the experimenters reminded the participant to exert a minimal amount of grip force, even if the device seemed fragile and heavy. It was done because, in previous studies carried out in the laboratory, participants naturally used an excessive amount of GF [14]. However, this behaviour led to a very limited amount of partial slips.

Between each trial, the glass plates were cleaned with alcohol in order to obtain images as clear as possible. It also allowed to remove the moisture from the finger on the glass that could alter the topography of the plates and thus, the friction. Meanwhile, the other experimenter added or removed the mass of the counterweight when necessary. The latter was hidden by a veil so that the subject could not observe this change (Fig 2.3.2). The weight change could happen at trial 3, 4 or 5 and occured only once a block in order to have normal trials in both cases - maximal and minimal weight (Fig 2.3.3) - within the same block. However, between each trial, the experimenter who was in charge to change the mass on the counterweight always behaved the same way. This was done so that the subject could not guess when the weight change occurred. The first trial with a different weight was called "weight catch trial".

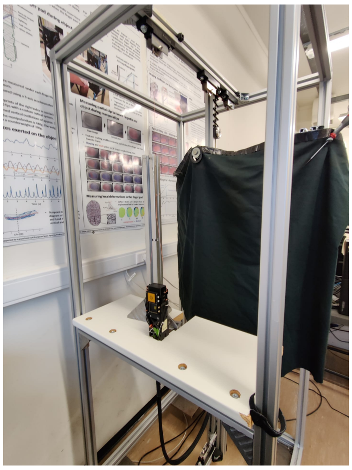

Figure 2.3.2: Experimental set-up and veil to hide the counterweight.

During each trial, the forces applied and the images of the index fingertip were recorded. At the end of the experiment, the friction coefficient among the participants' fingers and both materials was measured, using the method described in A. Barrea et al. paper [35]. For this purpose, the manipulandum was on the table and participants had to rub their index and thumb back and forth on the glass plates. This had to be done for three periods of fourteen seconds at different levels of normal forces. The range of normal forces for the three periods was respectively around 1 N, around 3 N and around 5 N. This task was performed at moderate speed and without releasing the grip. This measurement was done at the end of the experiment so that the participants could not guess that two different materials were used.

The total time of the experiment was approximately two hours, including the explanations.

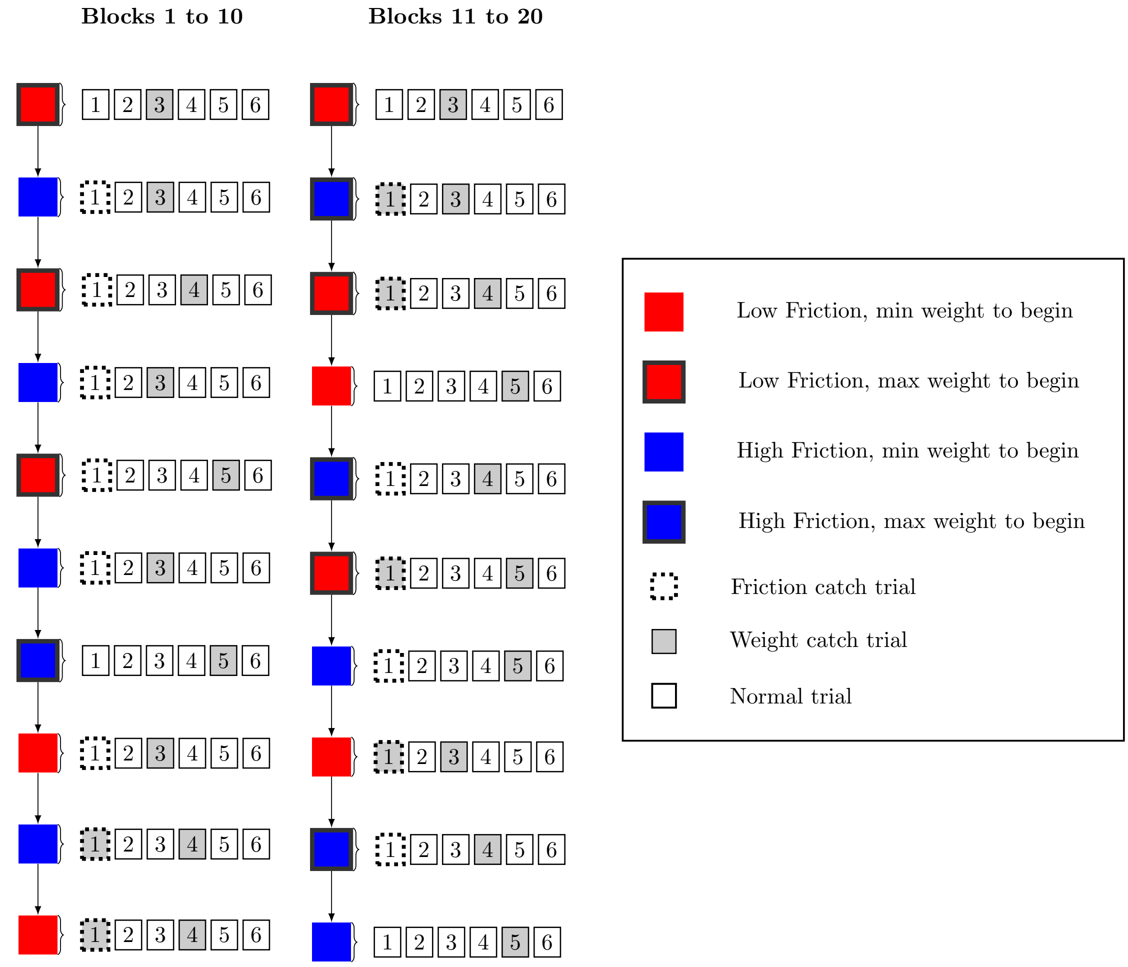

Figure 2.3.3: Protocol of the experiment. Participants performed twenty blocks of six trials each. The first two blocks were adaptative. Transparent plates with high and low friction properties were interchanged pseudorandomly, without the participant noticing it. If there was a change in friction, it was for the first trial of the new block. This trial was called "friction catch trial". Within the block, a mass was added or removed on the counterweight once only per block, changing the weight of the manipulandum for the rest of the block. Again, this change was made without the participant seeing it. The first trial with a different weight was called "weight catch trial". At the first trial of some blocks, there was a double catch (weight and friction). Those were not taken into account. All other trials are called "normal trials".

## 2.4 Data analysis

As explained in section 2.2, *Active Touch* allowed the measurement of the forces exerted by the thumb and the index fingers and an optical distance sensor gave information about the position of the counterweight - and then of the manipulandum - throughout the trial. Moreover, a camera collected images of the index fingerprint. All those data signals and images were processed with the programming and numeric computing platform MATLAB [45]. Several functions already developed by previous researchers were used in this study. Those are available in the *libactivetouch* and *imagetools* toolboxes. Other functions were created and are available on github [46].

### 2.4.1 Forces and position

Forces and position data were collected with a sampling rate of 200 Hz. They were filtered with a fourth-order low-pass Butterworth filter with a cut-off frequency of 20 Hz in order to suppress parasitic noise. The **grip force** is defined as the mean of the forces normal to the surface of the manipulandum exerted by the index and the thumb (eq. 2.4.1) [14]. The **load force** is defined as the norm of the sum of the forces applied tangentially to the surfaces of the manipulandum by each finger [14]. It is composed of two components: vertical (LFv) and horizontal (LFh) as represented in equation 2.4.2. The load force normally results from the weight of the object and the inertial forces (eq. 2.4.3). Force definitions are illustrated in figure 2.4.1.

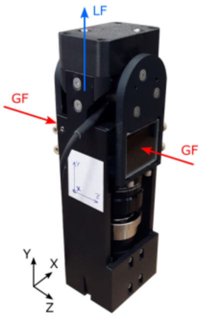

Figure 2.4.1: Picture of the manipulandum with definition of the GF and the LF. The reference frame is also shown. Modified figure from [37].

$$GF = \frac{GF_{thumb} + GF_{index}}{2} \tag{2.4.1}$$

$$\begin{aligned} LFv &= LFv_{thumb} + LFv_{index} \\ LFh &= LFh_{thumb} + LFh_{index} \\ LF &= \sqrt{LFv^2 + LFh^2} \end{aligned} \tag{2.4.2}$$

$$LF = ma + mg \tag{2.4.3}$$

In order to be able to compare trials with each other, all force signals were aligned to the instant when the load force was equal to 2 N. Then, the zero corresponded to this point. This force was associated to the first moment at which the participant could realize that the manipulandum weight was different. Indeed, it corresponded to the lowest weight of the device. Therefore, if the LF was equal to 2 N and the object did not rise, the subject could be aware that the weight was greater.

As explained in section 2.3, at the end of the experiment, the **static friction coefficient** among participants' fingers and both materials was measured. It was an important parameter since it determined the minimum grip force to be applied so that the object did not slip. The measurement of this parameter was done by applying the method of Barrea et al. [35]. In precision grip, the static coefficient of friction ($\mu_{static}$) is defined as the ratio of the tangential force over the normal force when the object starts slipping. Therefore, the slip onset should be accurately detected on each movement. In this method, the slip points are considered as the points for which the ratio of tangential force over normal force (TF/NF) is maximal. It seemed to be a good indicator of the slip onset because the static coefficient of friction is larger than the dynamic one. Therefore, the tangential force and the ratio TF/NF decreased slightly at slip onset [14, 35]. In conclusion, in this work, the maximum of the TF/NF ratio was the estimation of the static coefficient of friction corresponding to the normal force applied at that moment. In order to quantify the relationship between $\mu_{static}$ and the normal force, a negative power law was fitted to the data (Fig 2.4.2). The relation is expressed in equation 2.4.4.

$$\mu_{static} = k \cdot (NF)^{n-1} \tag{2.4.4}$$

Parameters $k$ and $n$ were obtained by using a least-squares regression procedure.

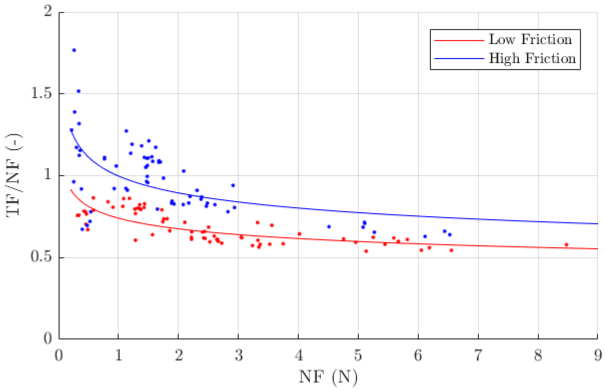

Figure 2.4.2: Coefficient of friction (TF/NF ratio) of the index finger as a function of grip force for an elderly participant obtained applying the method of Barrea et al. [35]. A negative power law was fitted to the data obtained by rubbing index and thumb back and forth on the glass plates. Red lines and dots refer to the low friction glass while blue lines and dots refer to the high friction glass.

The mean coefficient of friction over the force range from 1 to 5 N was calculated for the thumb and index fingers, for both glasses. Then, the data were averaged across both fingers. Given that a part of the work was to observe behavioural adaptation to changes in friction, a sufficient difference between glasses was required. The lower bound was fixed at 10%. This value was chosen based on the study of F.Schiltz et al. [14]. Participants with a lower relative difference between glasses were excluded from the analysis studying the adaptation to friction.

## 2.4.2 Images processing

Images were collected at 100 frames per second (fps) with a camera. Their dimensions were 1696 x 1248 pixels. The resolution was 4096 pixels/mm$^2$, which corresponds to an area of 26.5 x 19.5 mm. Although recorded, images of the first ten seconds (which correspond to the placement of the fingers on glasses) have not been studied in this work. Indeed, images of interest in the context of this study were those taken during the lift and the static phase. To that end, images within the time range 10 to 13.6 seconds for each trial were studied. Only one out of two images was preserved, which makes 180 frames per trial. Fingerprint images were processed to measure surface strains and to identify slips.

### Strain rates

In order to measure the skin strain rates from the images, a previously described pipeline [44, 47] was used. Briefly, the contact area between the fingertip and the glass plate was determined semi-automatically. Inside this area, optimal feature points were sampled in the initial frame of the sequence. They were then tracked forward and backward from frame to frame. On the basis of the trajectory of the feature points within the contact zone, the displacement field was computed. From the latter, strains within the contact area were computed. A Delaunay triangulation of the feature points sampled in the first frame was computed. For each triangle, gradients of the displacement field were derived and used to compute the strain rate (i.e. the strain resulting from the displacement between two consecutive frames [44]) components :

- $\varepsilon_{xx}$ : axial strain rate component along the x axis (horizontal).
- $\varepsilon_{yy}$ : axial strain rate component along the y axis (vertical).
- $\varepsilon_{xy}$ : shear strain rate component.

Strain rates computed for a given triangle were attributed to the center of this triangle. Then, the norm of the strain rate was calculated (eq. 2.4.5). It was a measure of the amplitude of the strain rate, no matter the orientation or the sign. [44].

$$\varepsilon_n = \left\| \begin{matrix} \varepsilon_{xx} & \varepsilon_{xy} \\ \varepsilon_{xy} & \varepsilon_{yy} \end{matrix} \right\| = \sqrt{\varepsilon_{xx}^2 + \varepsilon_{yy}^2 + 2\varepsilon_{xy}^2} \tag{2.4.5}$$

Finally, the strain rate norm was averaged for each participant and each condition. The detection of the contact area as well as an example of feature points used to compute the displacement field is shown in figure 2.4.3.

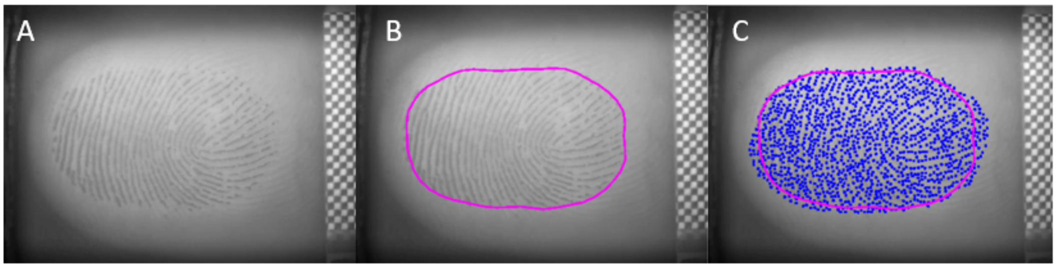

Figure 2.4.3: Images analysis. **A:** Raw image of the index finger obtained through the optical system of the manipulandum. **B:** Same image as A on which the contour of the contact area is depicted in pink. **C:** Same image again. Blue points represent the feature points which are tracked from frame to frame in order to obtain the displacement field. One can see some points outside the contact area. This is because during the lift-off movement, some points will enter the contact zone while others will leave it.

### Full slip trials

In order to check if there was full slip of the fingers relative to the glass during a trial, the total displacement of each triangle center within the contact zone was computed by comparing the displacement between the last and the first frame. We then looked at the first percentile of the displacement, for each trial of each participant. This concept of statistic meant that 1% of the data were equal or below this value of displacement. When this value exceeded 0.1 mm, the trial was considered as a full slip trial (all points slipped relative to the plate). Trials of this type were included in the strain analysis like all other trials.

### 2.4.3 Inspection of data

The first two blocks of each participant were considered as training blocks. Indeed, participants had to become familiar with the manipulandum and the movement to be performed. Moreover, trials with double catch (i.e. weight catch and friction catch in the same time - 6 trials) were not taken into account in those analyses. The results obtained during these trials could not be included in the simple catch analyses, because of the risk of biasing them. Also, the first trial of blocks for which there was no change (4 trials) were not considered as normal trials. Indeed, as there was a pause time, it could also bias the results. Overall, all participants completed the experiment well, except one subject from the elderly group. The kinematics being too far from the expected one, this participant was excluded from the analysis. Then, only 12 elderly subjects were taken into account. Regarding the images, some were unusable due to the poor quality. Thirteen young subjects had correct images and eight older participants had usable ones.

### 2.4.4 Statistical analysis

In order to determine if the difference between two conditions (catch and normal) was significant, Generalized Linear Mixed-Effects models (GLME) were used (function *fitglme*, MATLAB [48]). This statistical model was choosen because it contains both fixed effects predictors and random effects. In our case, fixed-effects predictors were the conditions (catch or normal trials) while random-effects terms were the participants. The latter allowed to account for GF differences that might exist due to subject-specific variations. The response variable of the model was the GF applied. GLME was applied for each time step of all trials and the p-value was extracted to evaluate if the condition had a significant effect. Knowing that the lower the p-value, the greater the statistical significance of the observed difference, the threshold was fixed at $p = 0.001$. It meant that the chances of wrongly declaring that the changes were significant was lower than 0.1%. This threshold was used given the large size of the sample.

# Chapter 3

# Results

First, a typical trial will be shown, as well as a comparison of the force applied. Then, we will compare the adapation to friction and weight of the two groups. As mentionned in the previous section, all trials were synchronised at the time when the LF was equal to 2 N. Therefore, the zero on the x axis was set to this point. This moment corresponded to the first time that the participant could realise that the weight of the object was different since the minimal weight is 2 N.

## 3.1 Typical trial

The evolution of the device position and forces applied by an elderly participant during a typical trial are shown in figure 3.1.1. The trial was divided into two movements and one static phase. The first movement was an upward movement of about 20 cm followed by a 1.5 seconds static phase. The last movement was a downward movement to replace the manipulandum on the table. The latter was not studied in this work and not included in the graphs. A typical upward movement included two LF peaks. The first one (positive) was related to the acceleration of the object and the second one (negative), appearing at the end of the first motion, was related to the slowing down of the manipulandum by the participants. It was partly due to the counterweight and the resulting high inertia. One could observe that each LF peak was paired with a GF peak. During the static phase, the LF remained fairly constant (2 or 3.1 N - object's weight) as did the GF.

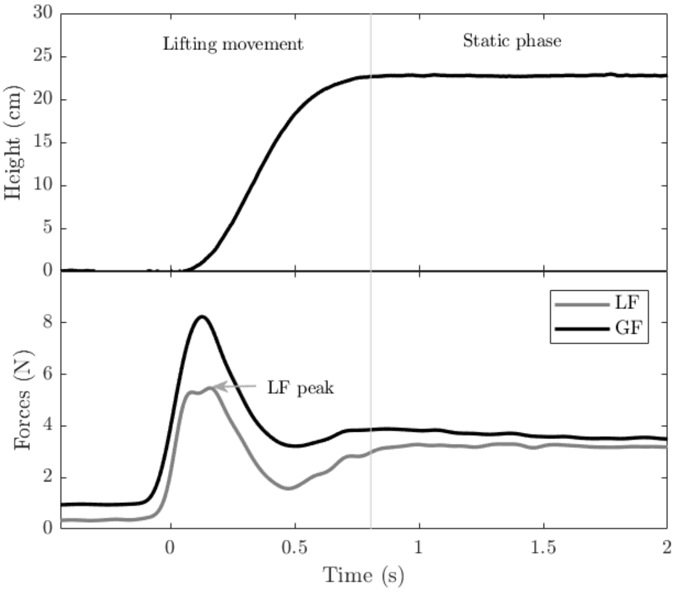

Figure 3.1.1: Evolution of the vertical position of the manipulandum and the forces applied during a typical trial. It consisted into one fast lifting movement followed by a static phase. The positive LF peak is related to the acceleration of the manipulandum and the negative one is due to the slowing down of the object by the participants because of the system inertia.

Before the two age groups could be compared, it was important to be sure that the kinematics of the movement were equivalent. To that end, the load forces evolution over time were checked for the two groups (Fig 3.1.2A-B). These were relatively similar and reinforced the idea that the kinematics were equivalent. The difference of applied GF between the two age groups was also compared. On average, the relative difference in GF was 106.86% during the static phase (two-sample t-test during the static phase, $p<0.001$). The standard deviation across subjects and within the same subject were also higher for elderly participants than for younger ones (Fig 3.1.2C-D). It could thus be concluded that older participants exerted higher forces than young participants during normal trials and that the variability across subjects and within the different trials of a same subject was more important for elderly participants.

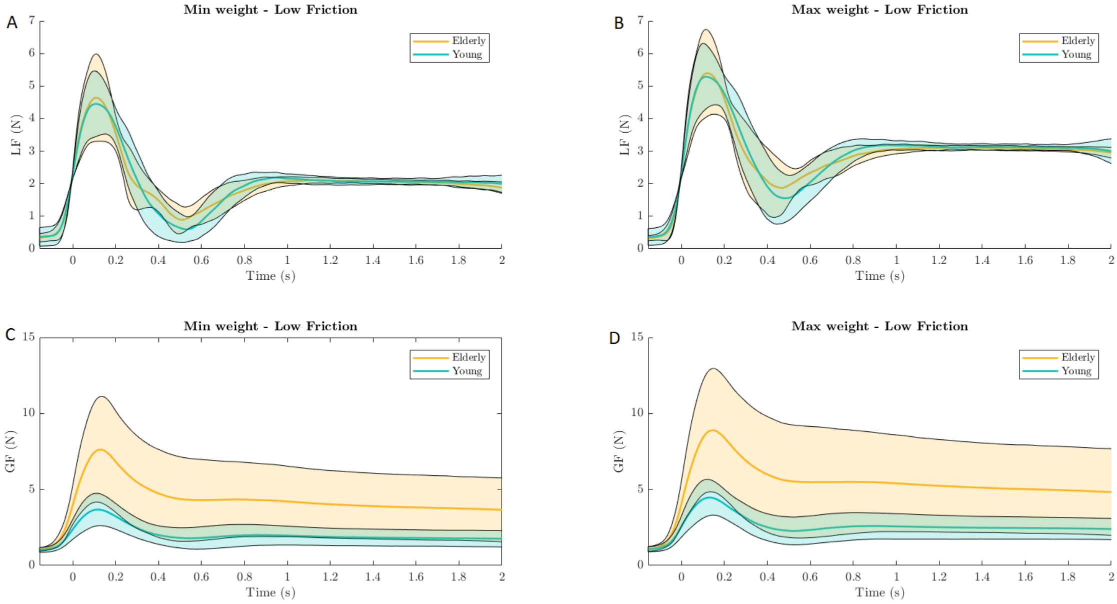

Figure 3.1.2: **A:** Evolution of LF as a function of time for minimal weight (i.e. 2 N) under low friction trials (n=16). **B:** Evolution of LF as a function of time for maximal weight (i.e. 3.1 N) under low friction trials (n=20). **C:** Evolution of GF as a function of time for minimal weight (i.e. 2 N) under low friction trials (n=16). **D:** Evolution of GF as a function of time for maximal weight (i.e. 3.1 N) under low friction trials (n=20). In all panels, orange lines are averages across elderly participants (n=12) while blue ones are averages across young subjects (n=15). Orange and blue shaded areas are the standard error of elderly and young participants respectively.

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## 3.2 Adaptation to friction

### 3.2.1 Difference in friction between the two sets of glasses

One of the goals of this work was to compare the adaptation of young and older people to friction. To this aim, glasses with different friction properties were interchanged. It was first necessary to verify that the difference in the coefficient of friction between the two materials was consistent. For this purpose, the static friction coefficient between the index/thumb of each participant and the two sets of glasses was measured, as explained in section 2.3, *Experimental procedure*. Note that none of the young participants noticed that different materials were used while two elderly subjects did. Following the method of Barrea et al. [35] (see section 2.4), the static friction coefficient was characterised over a GFs range 1 to 5 N, for the thumb and index fingers. The curves of all participants obtained with this method for the index finger were reported in the appendix A. The mean coefficient of friction over this range was calculated and the data were averaged across both fingers. A single point for each participant was thus obtained, as shown in figure 3.2.1.

For both age groups, we observed that the coefficient of friction was always higher in the case of the high friction glasses. Overall, elderly participants had a lower friction coefficient than young ones. The average relative difference between friction coefficients was higher for the elderly group than for the young one (42.96 and 14.92% respectively). Given that a part of the work was to observe behavioural adaptation to changes in friction, a sufficient difference between glasses was required. The lower bound was fixed at 10%. This value was chosen based on the study of F.Schiltz et al. [14]. Participants with a lower relative difference in friction between glasses were excluded from the analysis studying the adaptation to friction. Accordingly, five participants from the young group were excluded because of the too low relative difference in friction (0.47, 2.41, 2.82, 4.47, 9.59%). In the elderly group, only one participant was excluded (7.96%). In summary, the two sets of plates showed a consistent difference in friction in the two groups, on average 14.92% for young participants and 42.96% for elderly ones. Overall, friction coefficients were lower for elderly participants. For more visibility, this graph is available for both groups separately in appendix B (Fig B.0.1).

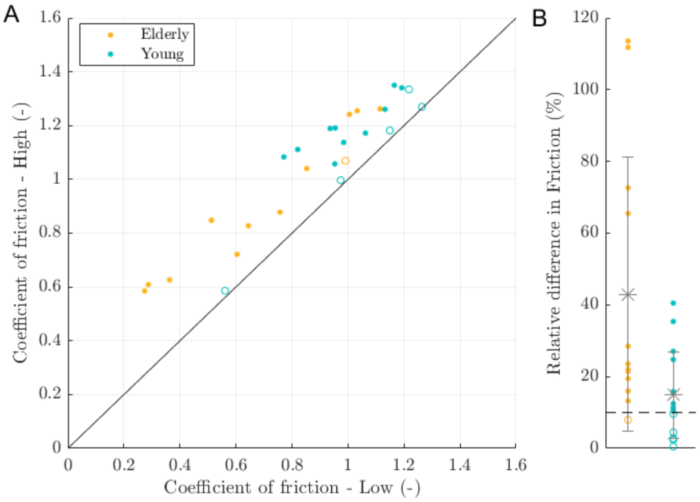


Figure 3.2.1: **A:** Mean coefficient of friction of both sets of glasses over the range 1-5 N for each participant ($n_{young} = 15$, $n_{elderly} = 12$). **B:** Relative difference in friction of the glasses over the interval 1-5 N, calculated with the mean of the values of the friction coefficient of both sets of glasses. Asterisks represent the average relative difference within each group and the grey lines represent the standard deviation in each group. The dashed line indicates the lower limit of sufficient difference in friction between glasses for the inclusion of a participant in the analysis. In panels A and B, one point corresponds to one participant. The data were averaged across both fingers. Orange points are for elderly subjects while blue ones are for young participants. Empty circles represent participants that had a relative difference in friction lower than 10% ($n_{young} =$ 5, $n_{elderly} = 1$). Then, those subjects were removed from the friction adaptation analyses.

### 3.2.2 Normal trials

First, we investigated if the two different materials led to different gripping behaviours. We compared the mean GF during the static phase of low friction normal trials with the one of high friction normal trials, i.e. those not following an unexpected change of friction or weight (Fig 3.2.2). Those analyses were performed only with participants who had a relative difference in friction higher than 10% ($n_{young}$=10, $n_{elderly}$=11). We found that all participants except one in each age category used a higher GF for the lower friction glass, no matter the manipulandum's weight. As one could observe in figure B.0.2 in the appendix B, participants with the smallest difference in GF were not the participants who had the smallest difference in friction. We could nevertheless say that participants of the two categories adjusted their GF to the friction level. However, the level of GF varied widely across subjects, especially in the older age group. The relative difference in GF for the elderly group was around 16% while for the young one, around 8.5% (weight had no real influence on this GF relative difference). It seemed logical that the relative difference in GF was higher for the elderly group since the relative difference in friction was also greater. However, in both groups, the mean GF difference was not of the same order of magnitude as the mean friction coefficients difference (42.96% and 14.92% for older and young group respectively). We concluded that the relative difference in GF for normal trials was higher for elderly than for young participants, as it was also the case for the friction difference. However, the GF relative difference was not of the same order of magnitude than relative friction difference. Also, the weight did not influence the relative change in GF for both groups.

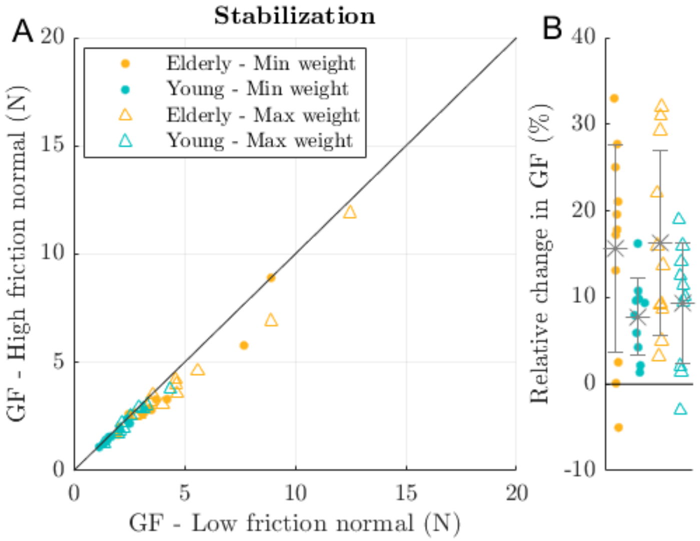


Figure 3.2.2: **A:** Mean value of GF during the static phase of normal trials for participants who had a relative difference in friction higher than 10% ($n_{young}$ = 10, $n_{elderly}$ = 11). **B:** Difference in GF during the static phase of normal trials, relative to the mean value of the GF for the two friction conditions. Asterisks represent the average relative difference within each group and the grey lines represent the standard deviation in each group. In panels A and B, one point/triangle corresponds to one participant. Orange markers are for elderly subjects while blue ones are for young participants. Dots represent normal trials under minimal weight (Low friction: n=16, High friction: n=17) while triangles are for normal trials under maximal weight (Low friction: n=20, High friction: n=18).

### 3.2.3 Friction catch trials

Second, as we observed an adaptation to friction for normal trials, we evaluated if there was already a change in GF behaviour during the static phase of friction catch trials. For this purpose, the mean GF during the static phase of friction catch trials was compared to the one of normal trials, associated with glasses with different properties. There were two types of friction catch trials:

1. *Low friction catch trial*: when previous trials were performed with the high friction glasses.
2. *High friction catch trial*: when previous trials were performed with the low friction glasses.

Regarding the low friction catch trials (Fig 3.2.3A-B), we found for both groups that the GF was, on average, already higher during the static phase under the two weight conditions (i.e. minimal and maximal weight). The mean relative change was higher for elderly participants than for young ones. Again, it seemed logical since the relative difference in friction was more important for elderly than for young people. The adaptation for older participants was more or less 42% (47.49% and 37.25% for minimal and maximal weight respectively). For young subjects, the adaptation was about 15% (9.07% and 20.06% for minimal and maximal weight respectively). For young participants, the difference was higher for the maximal manipulandum weight condition, it was the reverse situation for elderly subjects. However, they were already familiar with the weight. In all cases, the relative differences in GF were of the same order of magnitude as the relative difference in friction for the two age groups (i.e. 42.96% and 14.92% for elderly and young subjects respectively). Within the elderly group, only two participants did not adapt to the friction. None of those two subjects corresponded to the one who did not adapt during normal trials. Within the young group, four participants did not adapt. It is important to note that for the low catch trials, it was normally necessary to increase the GF level because the reduction of friction increased the risk of slipping and dropping the object.

Regarding the high friction catch trials (Fig 3.2.3C-D), there was no emergency to adapt the GF level since the friction increased. Therefore, the risk of slippage was reduced compared to the previous trials with low friction glasses. This was reflected in the results. Indeed, we observed that the adaptation of both groups was less clear than for the catch in the other direction. The only case for which we could perhaps talk about an adaptation was for the elderly group, under maximal manipulandum weight (-7.61%). In this condition, only two elderly participants did not adapt. We could conclude that, given the less urgent need for adaptation, participants took more time to adapt to the high friction condition.

In brief, participants from both group adapted the GF to the low friction condition and this adaptation was already present during the static phase of low friction catch trials. However, adaptation to high friction condition was less clear for high catch trials. Again, the case-by-case analysis is accessible in appendix B (Fig B.0.3).

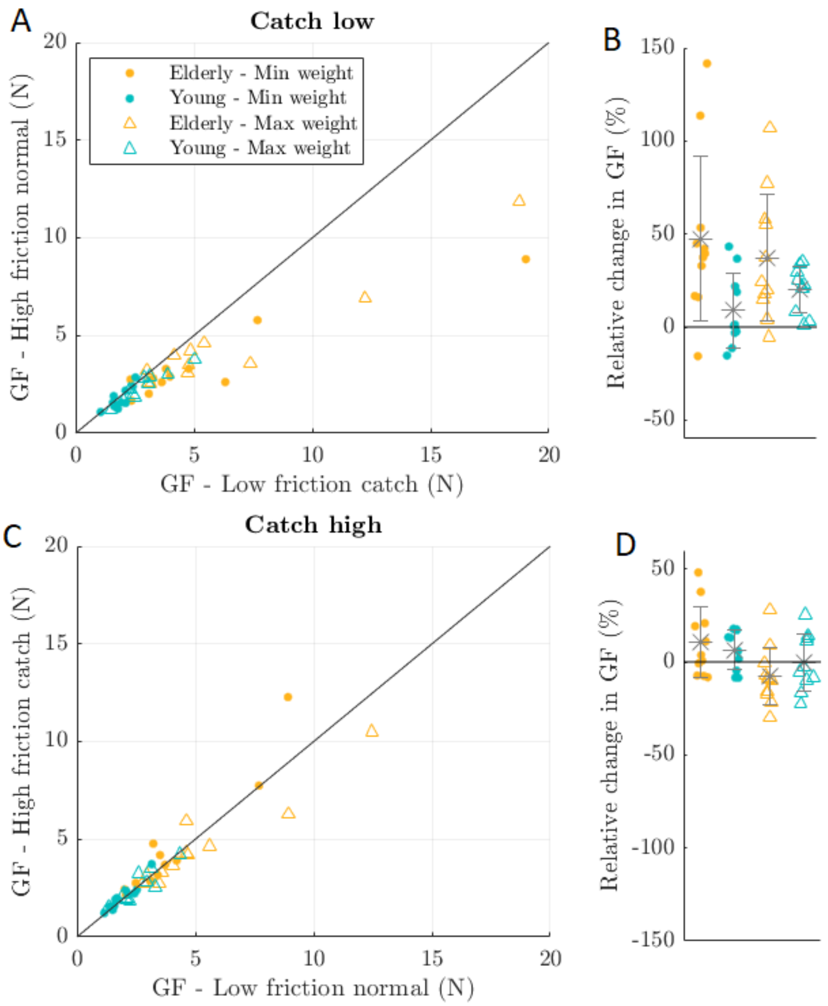


Figure 3.2.3: **A:** Mean value of GF for each glass during the static phase of low friction catch trials ($n_{max}$=2, $n_{min}$=1) and high friction normal trials ($n_{max}$=18, $n_{min}$=17) for participants who had a relative difference in friction higher than 10% ($n_{young}$ = 10, $n_{elderly}$ = 11). **B:** Relative difference in GF between the mean GF of the static phase of low friction catch trials and high friction normal trials. **C, D:** Same as A, B except that the static phases of high friction catch trials ($n_{max}$=2, $n_{min}$=3) are compared to the static phases of low friction normal trials ($n_{max}$=20, $n_{min}$=16). In panels A, B, C, D one point/triangle corresponds to one participant. Orange markers are for elderly subjects while blue ones are for young participants. Dots represent trials with minimal weight while triangles are for trials with maximal weight. For B and D, asterisks represent the average relative difference within each group and the grey lines represent the standard deviation in each group.

### Time of the GF adjustments to friction

Since we observed that, especially for low friction catch trials, the GF was already adjusted to friction level during the static phase, we investigated the temporal evolution of the GF during friction catch trials to determine the time at which significative changes in GF occured (Fig 3.2.4 and 3.2.5). The first thing that we observed was that, in both groups, participants produced movements with very similar kinematics across conditions, as shown by the LF curves (first rows of each panel, Fig 3.2.4 and 3.2.5). The LF curves were also similar between the two age groups, although the standard deviation across subjects associated with those LF curves was more important for the elderly group.

For the low friction catch trials under minimal weight (Fig 3.2.4A-B), no significant GF difference between the two conditions was found for the young group (Fig 3.2.4A). However, we could observe that the relative difference in GF remained positive over time, which meant that the GF applied during low catch trials was, on average, higher than during high friction normal trials. It was important to notice that in this condition, four young participants did not adapt during the static phase of low friction catch trials (Fig 3.2.3A-B). Then, they had an influence on the temporal mean GF curve. For elderly participants, the significant GF difference was found at 0.09 seconds ($\Delta$GF=31.32%) after the 0 (LF=2N) (or 623 ± 195 ms after the sound indicating to the partipant to lift the manipulandum). Then, significant difference appeared during the lifting of the object. After that moment, the difference between the two conditions remained significant over time ($p < 0.001$). In this condition, only one older participant did not adapt. For both groups, the maximal GF difference was reached during the deceleration of the object (~25% and ~60% for young and elderly group respectively).

For the low friction catch trials under maximal weight (Fig 3.2.4C-D), significant GF difference between the conditions was found for both group ($t_{young}$ = -0.095 s, $\Delta$ $GF_t$=12.93% and $t_{elderly}$ -0.025 s, $GF_t$=22.17%). Therefore, before the time at which the manipulandum was set in motion. It corresponded respectively to 383 ± 132 ms and 508 ± 195 ms after the sound indicating to lift the manipulandum. For young participants (Fig 3.2.4C), we could observe that during the acceleration, the difference was not significant anymore but became so again during the deceleration phase. From this moment, it remained significant over time. For elderly participants (Fig 3.2.5D), on the contrary, the GF difference remained significant over time. Again, for both groups, the highest $\Delta$GF was found during the deceleration phase (~30% and ~50% for young and elderly participants respectively). For the young group, the maximal $\Delta$GF was a little bit higher than under minimal weight. It was the opposite for the elderly group (Fig 3.2.6).

For the high friction catch trials under minimal weight (Fig 3.2.5A-B), a signifiant GF difference was found for young participants, but not in the logical way. Indeed, if there was an adaptation, the $\Delta$GF should have been negative as the friction increased. However, it was consistent with the previous obtained results (Fig 3.2.3C-D) since the GF relative difference during static phase was also positive instead of negative. For eldery participants, no significant relative difference in GF was found. However, we could also observed that the $\Delta$GF was positive, as for young participants. Again, it was in accordance with what we found in previous analyses.

For the high friction catch trials under maximal weight (Fig 3.2.5A-B), no significant difference in GF was found, for both young and elderly participants. However, in this case, the sign of the $\Delta$GF was consistent with the friction change (less force applied since higher friction). For elderly participants, the highest GF difference was again found during the deceleration phase.

In summary, we found that, for the older group, GF during low friction catch trials reached a level that was significantly different from the level of high friction normal trials (between 500 and 630 ms after the sound indicating to lift the object). For young participants, it was also the case but only under maximal manipulandum weight ($\sim$ 380 ms after the sound indicating to lift). The $\Delta$GF was always more important for the elderly group than for the young one (Fig 3.2.6). It was consistent since the relative difference in friction was also more important. The maximal $\Delta$GF was reached more or less at the same time for both group (i.e. during the deceleration phase). However, for young participants, the GF difference was higher under maximal weight than under minimal weight. It was the opposite for elderly participants (Fig 3.2.6). For high friction catch trials, results were less consistent. However, there was no emergency in this condition since the risk of fall was decreased compared to previous trials. Under minimal weight, both groups did not adapt. Under maximal weight, the $\Delta$GF was negative but a significant difference between conditions was never reached. The relative difference in GF was also higher for elderly participants in this condition (Fig 3.2.6). All the results are summarized in table 3.1.

| | | | **Young** | **Elderly** |
|---|---|---|---|---|
| Friction coefficients | | Relative diff (%) | 14.92 | 42.96 |
| Normal trials | Min weight | GF diff (%) | 7.80 | 15.65 |
| | Max weight | | 9.31 | 16.29 |
| Low friction catch | Min weight | GF diff (%) | 9.07 | 47.49 |
| | Max weight | | 20.06 | 37.25 |
| High friction catch | Min weight | | 6.39 | 10.66 |
| | Max weight | | -0.35 | -7.61 |
| Low friction catch | Min weight | Time (ms) | - | 623 ± 195 |
| | | GF diff (%) | - | 31.32 |
| | Max weight | Time (ms) | 383 ± 132 | 508 ± 195 |
| | | GF diff (%) | 12.93 | 22.17 |
| High friction catch | Min weight | Time (ms) | 115 | - |
| | | GF diff (%) | 14.91 | - |
| | Max weight | Time (ms) | - | - |
| | | GF diff (%) | - | - |

Table 3.1: Comparison young/elderly - Adaptation to friction. The time taken up has as reference the sound instructing the participant to lift the manipulandum. Red is to underline the fact that participants did not adapt. Then, this result could be ignored.

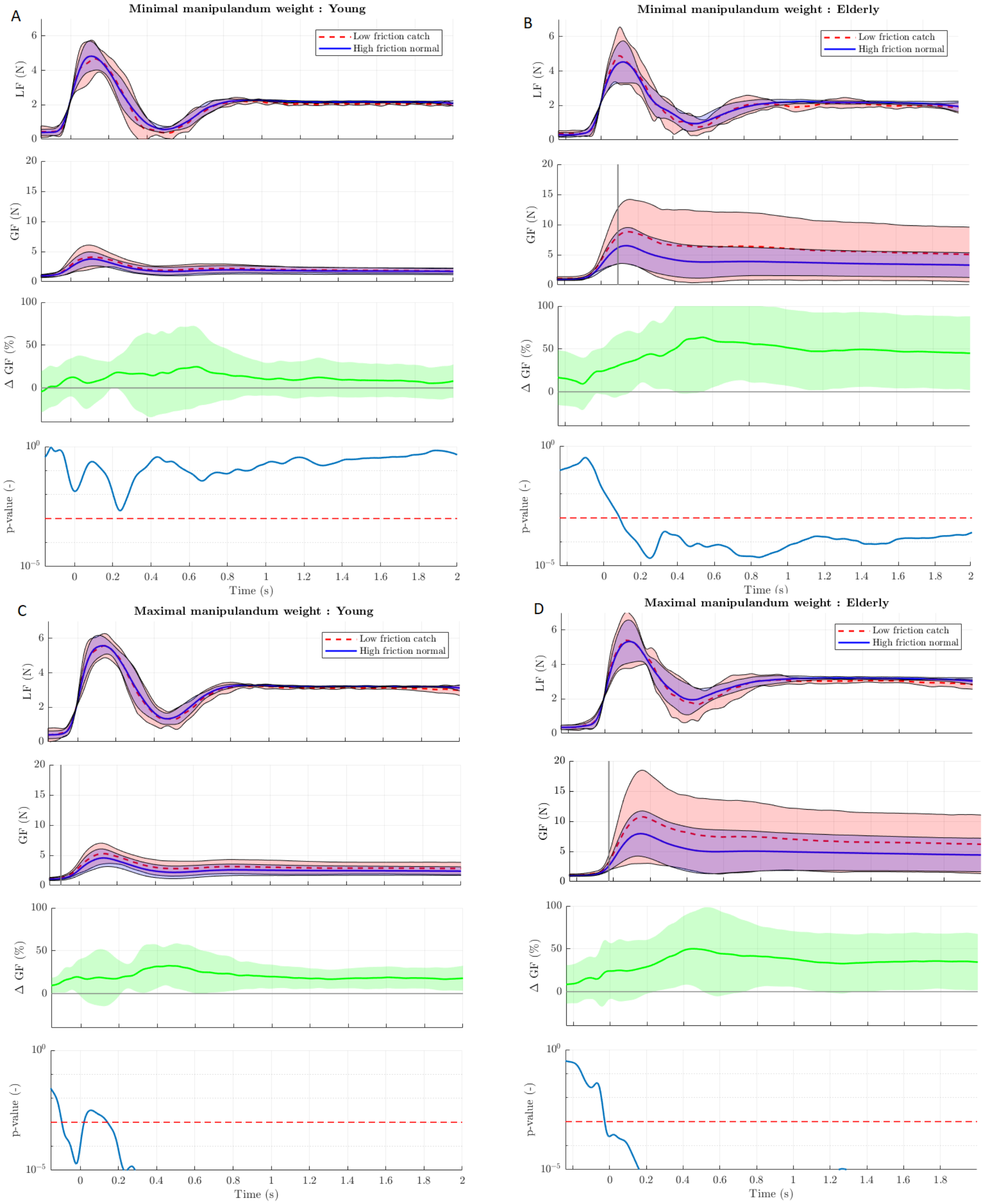


Figure 3.2.4: **A:** Evolution of LF, GF, GF difference and p-value as a function of time for the first movement of low friction catch trials under minimal weight (n=1) for young participants who had a relative difference in friction higher than 10% (n=10). Trials are synchronised at the moment when the LF is equal to 2 N (i.e. minimal weight of the manipulandum). 0 second corresponds to that point. Lines are averages across participants and shaded areas are the standard deviation across participants. Red is for low friction and blue is for high friction. Continuous traces are normal trials and dashed lines are friction catch trials. The grey line shows the time of the statistically significant difference between GF curves (GLME, $p<0.001$). The third panel shows friction catch GF minus normal trials GF. The red dash-dotted line in the lower panel shows the threshold below which the difference is significant. **B:** Same as A for elderly participants who had a relative difference in friction higher than 10% (n=11). **C:** Same as A for low friction catch under maximal weight (n=2). **D:** Same as C for elderly participants.

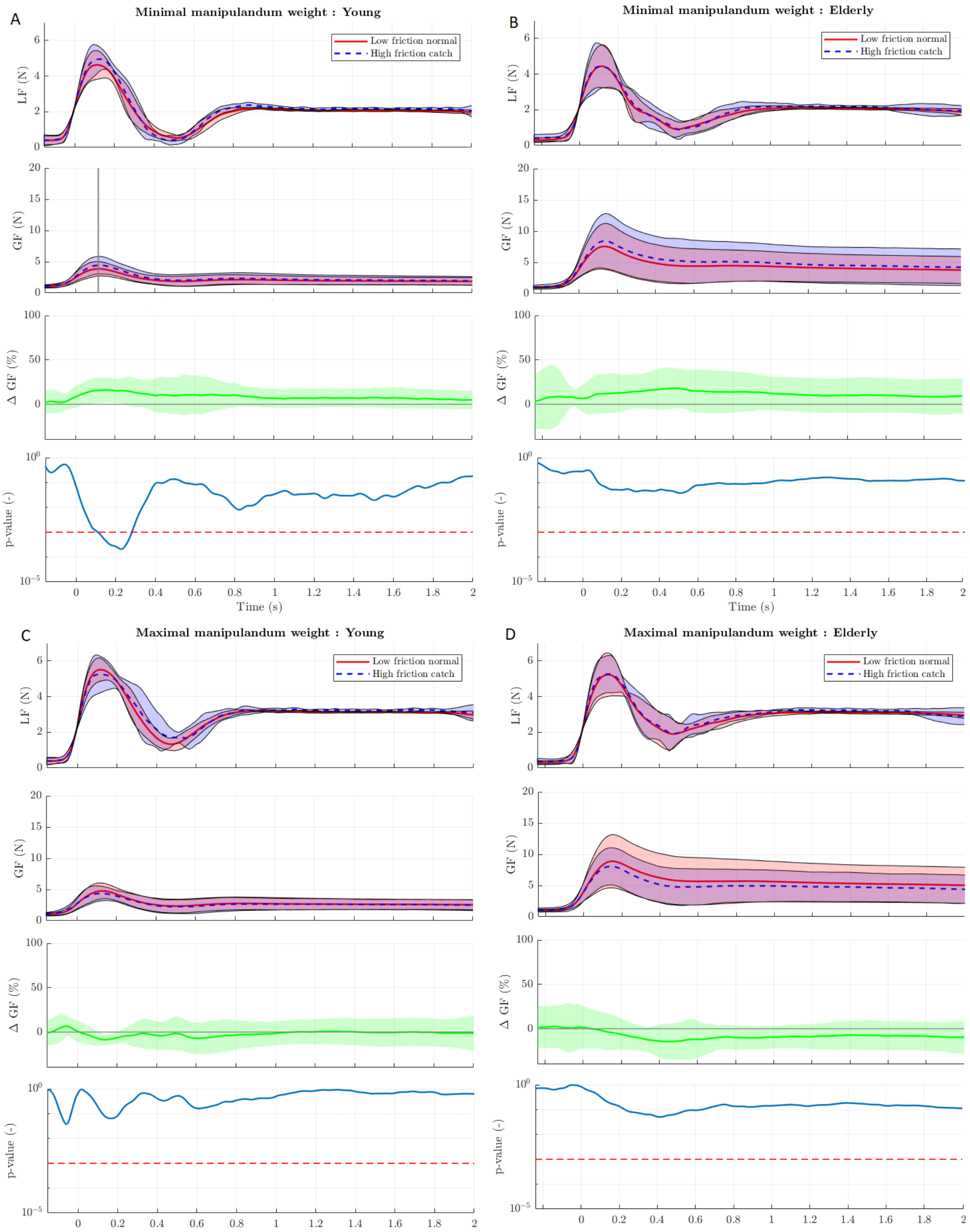


Figure 3.2.5: **A:** Evolution of LF, GF, GF difference and p-value as a function of time for the first movement of high friction catch trials under minimal weight (n=3) for all young participants who had a relative difference in friction higher than 10% (n=10). Trials are synchronised at the moment when the LF is equal to 2 N (i.e. minimal weight of the manipulandum). 0 second corresponds to that point. Lines are averages and shaded areas are the standard deviation across subjects. Red is for low friction and blue is for high friction. Continuous traces are normal trials and dashed lines are friction catch trials. The grey line shows the time of the statistically significant difference between GF curves (GLME, $p<0.001$). The third panel shows friction catch GF minus normal trials GF. The red dash-dotted line in the lower panel shows the threshold below which the difference is significant. **B:** Same as A for elderly participants (n=10). **C:** Same as A for high friction catch under maximal weight (n=2). **D:** Same as C for elderly participants.

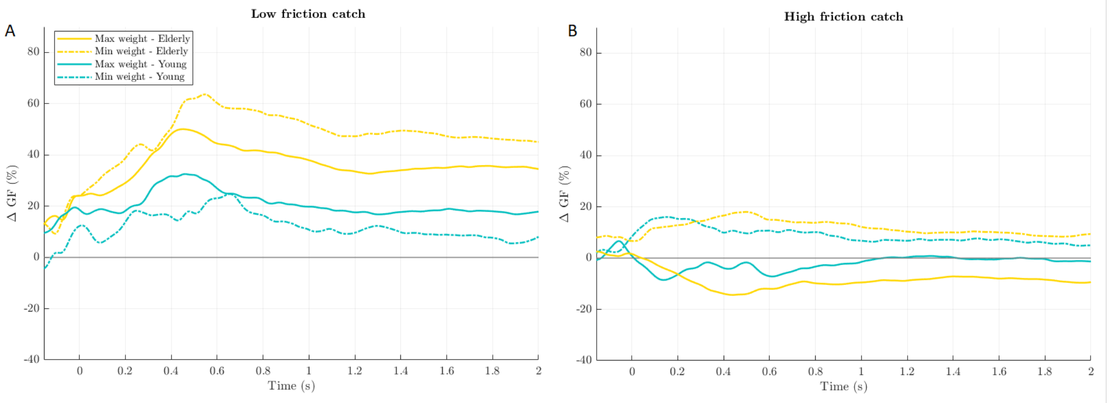


Figure 3.2.6: **A:** Evolution of ΔGF as a function of time for the first movement of low friction catch trials, for young and elderly participants who had a relative difference in friction higher than 10% ($n_{young}$=10, $n_{elderly}$=11). Orange lines represent elderly participants while blue ones represent young participants. Continuous traces are trials under maximal weight while dotted traces are trials under minimal weight. **B:** Same as A but for high friction catch trials.

## Images analysis

The responses of participants to low friction catch trials suggested that a sensory signal about the frictional properties of the glasses could have been sent to the CNS. To confirm this hypothesis, the skin strain rate norm associated to partial slips was computed for the different conditions. As for the GF analysis, we looked at the difference in strain rate norm between the catch and the normal conditions. The LF curves visible in figures 3.2.7 and 3.2.8 were plotted only with participants whose images were analysed and who had a relative difference in friction higher than 10%.

The first element that we could notice was that, in all conditions, the strain rate norm was higher for young participants than for older ones, especially during the lifting of the object. However, for elderly people, we could observe two peaks, corresponding to the acceleration and deceleration phases. For young people, only the peak linked to the acceleration phase was visible in the strain rate norm curves.

For low friction catch trials under minimal weight, we observed in the previous analysis that there was no significant GF difference for young participants. In figure 3.2.7A, one could observe that the strain rate norm curves were not so different between the two conditions. For elderly participants, the strain rate norm curve for low friction catch trials remained above the one of high friction normal trials throughout the movement. In the previous analysis, we observed significant GF difference during the acceleration of the manipulandum (Fig 3.2.4B). However, it was for all subjects and not all had analysable images. In appendix C (Fig C.0.1), GF curves of participants who had analysable images (i.e. good quality images) only were plotted and we could see that the relative difference in GF was only significant at 0.215 s (after the 0) while the strain rate norm difference became significant at 0.21 s. Then, significant difference in strain rate norm appeared before the significant difference in GF.

For low friction catch trials under maximal weight, we could clearly observe in both groups that the strain rate norm curve of low friction catch trials was higher than the one of high friction normal trials at the time of the LF peak (at $\sim 0.18$ s). This difference was significant for young participants but not for elderly subjects. For young participants, we observed in the previous analysis that the GF difference was also significant in this condition but at the very beginning of the movement. However, we could observe that the GF difference was only significant again during the acceleration phase. If we looked at the GF curves of participants with images (appendix C, Fig C.0.1), we could see that the difference in GF was significant from the beginning, and remained so. Then, they seemed to adapt to the friction before the difference in strain became significant.

For high friction catch trials under minimal weight (Fig 3.2.8A-B), we observed in the previous analysis that there was no adaptation for both groups. The GF curves corresponding to high friction catch trials were even above those of low friction normal trials. This coincided with what we observed in the image analysis since in both cases, the strain rate norm seemed to be more important during high friction catch trials.

For high friction catch trials under maximal manipulandum weight (Fig 3.2.8C-D), the same observation as under minimal weight was done for the young group. Indeed, strain rate norm curve of high friction catch trials were above those of low friction catch trials. However, for elderly participants, the two strain rate norm curves were very close to each other. Nevertheless, in the previous analysis, we observed a negative difference in GF between the two conditions, although no significant.

To conclude, fingerpad strain rate norms were overall higher for young participants than for older ones. In the case of low friction catch trials, strain rate norms were higher than during high friction normal trials (except for the young group under minimal weight). About the strain rate norm curves for high friction catch trials, results were not consistent. However, it was also the case in the previous analysis.

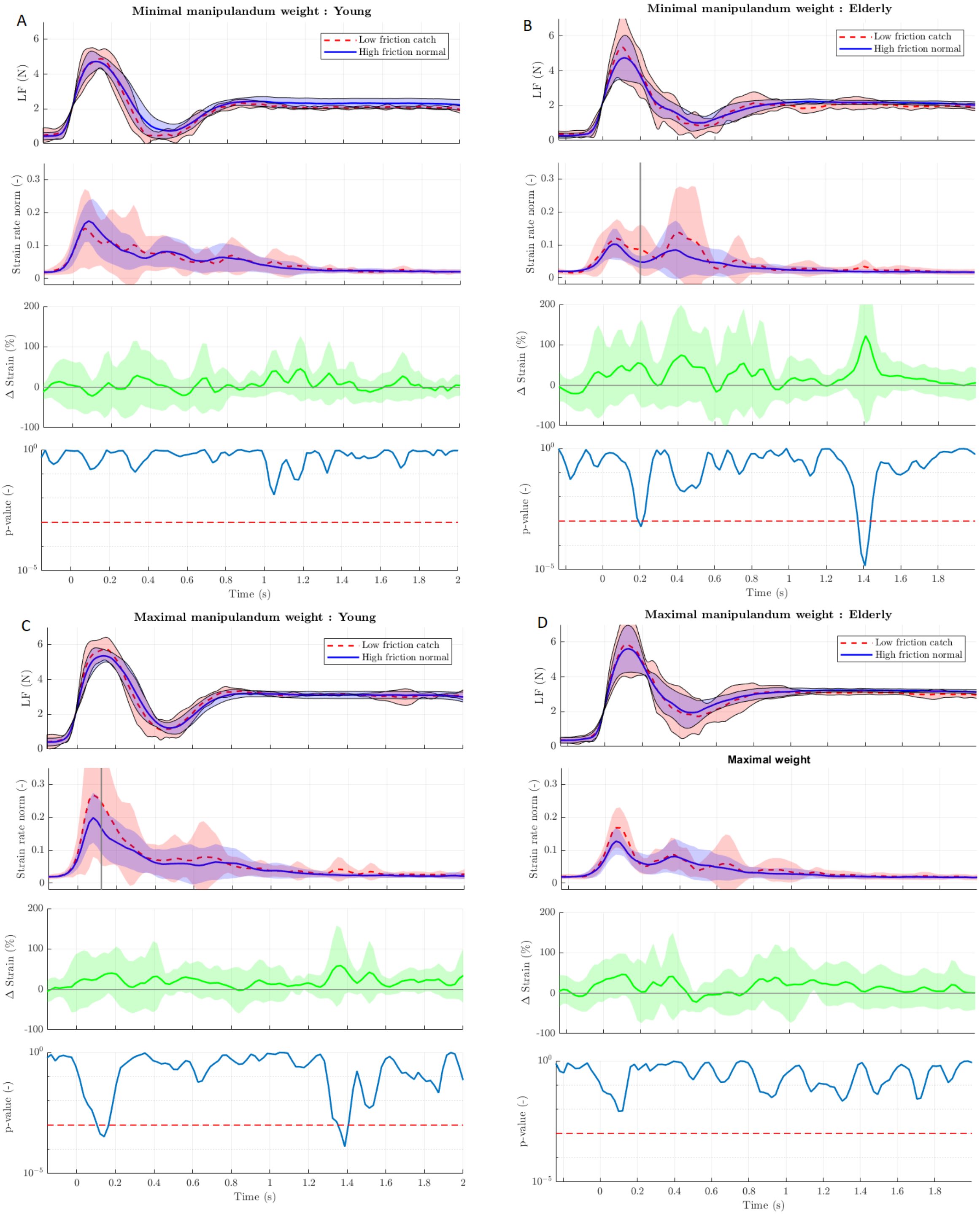


Figure 3.2.7: **A:** Evolution of LF, strain rate norm, strain rate norm difference and p-value as a function of time for the first movement of low friction catch trials under minimal weight (n=1) for young participants who had analysable images and a relative difference in friction of minimum 10% (n=8). Trials are synchronised at the moment when the LF is equal to 2 N (i.e. minimal weight of the manipulandum). 0 second corresponds to that point. Lines are averages across participants and shaded areas are the standard deviation across subjects. Red is for low friction and blue is for high friction. Continuous traces are normal trials and dashed lines are friction catch trials. The grey line shows the time of the statistically significant difference between GF curves (GLME, $p<0.001$). The third panel shows friction catch minus normal trials. The red dash-dotted line in the lower panel shows the threshold below which the difference is significant. **B:** Same as A for elderly participants who had analysable images and a difference in friction higher than 10% (n=7). **C:** Same as A for low friction catch under maximal weight (n=2). **D:** Same as C for elderly participants.

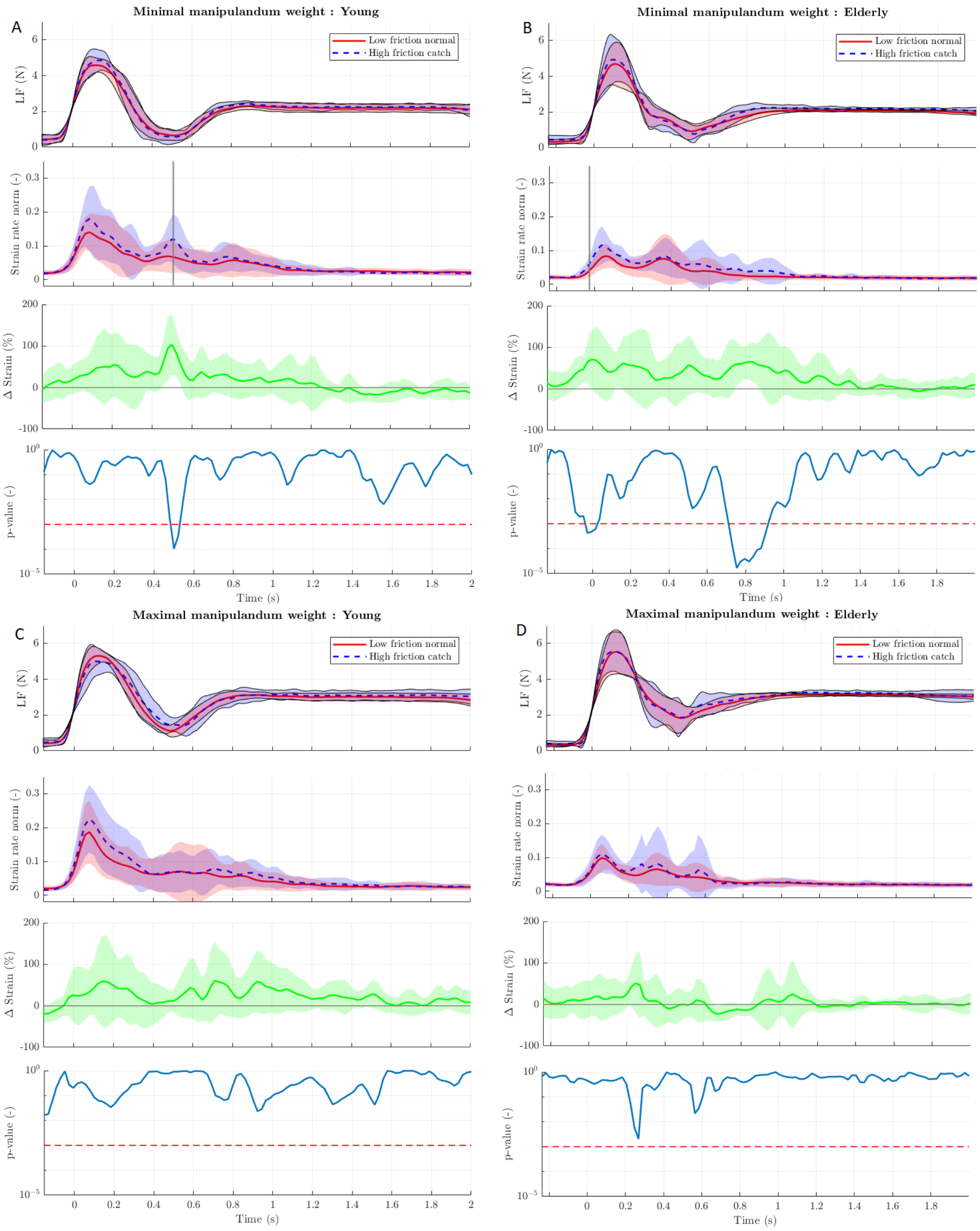


Figure 3.2.8: **A:** Evolution of LF, strain rate norm, strain rate norm difference and p-value as a function of time for the first movement of high friction catch trials under minimal weight (n=3) for young participants who had analysable images and a difference in friction higher than 10% (n=8). Trials are synchronised at the moment when the LF is equal to 2 N (i.e. minimal weight of the manipulandum). 0 second corresponds to that point. Lines are averages across participants and shaded areas are the standard deviation across subjects. Red is for low friction and blue is for high friction. Continuous traces are normal trials and dashed lines are friction catch trials. The grey line shows the time of the statistically significant difference between strain rate norm curves (GLME, $p<0.001$). The third panel shows friction catch minus normal trials. The red dash-dotted line in the lower panel shows the threshold below which the difference is significant. **B:** Same as A for elderly participants who had analysable images and a relative difference in friction higher than 10% (n=7). **C:** Same as A for maximal weight catch under high friction (n=5 attention à changer). **D:** Same as C for elderly participants.

## 3.3 Adaptation to weight

The second goal of this work was to compare the adaptation to weight of young and older people. Unlike friction changes, the majority of subjects noticed that weight changes occured during the experiment. However, they were not able to observe exactly when they took place as they were quite subtle and unpredictable. The mass added/removed of the existing counterweight was 110 g. Then, the apparent manipulandum weight was 2 N or 3.1 N. For the analysis of the adaptation to weight, we followed the same procedure as for the study of the adapation to friction. However, all subjects were included in the analyses ($n_{young}$=15, $n_{elderly}$=12).

### 3.3.1 Normal trials

First, we verified that a higher weight led to a higher GF during normal trials. This analysis was performed during the static phase (Fig 3.3.1). We found that all participants, in both age groups, used a higher GF for the maximal weight. It seemed logical since the LF, which was equal to the object's weight during the static phase (eq 2.4.3), was higher (i.e. 3.1 N vs 2 N). We could observe that the GF level varied widely across subjects, in the two categories. The GF relative difference was around 30% for elderly subjects (29.36 and 29.57% for low and high friction respectively) and around 35% for young participants (35.09 and 34.57% for low and high friction respectively) if mean GF during minimal weight trials was the reference. If mean GF during maximal weight trials was the reference, we found ∼25% and ∼22% for young and elderly respectively. We concluded that the weight clearly influenced the GF level during the static phase of normal trials for both groups. The mean GF difference between the two conditions was a little bit higher for young participants (∼35%) than for elderly subjects (∼30%). However, in both groups, the relative difference in GF was not influenced by the friction condition.

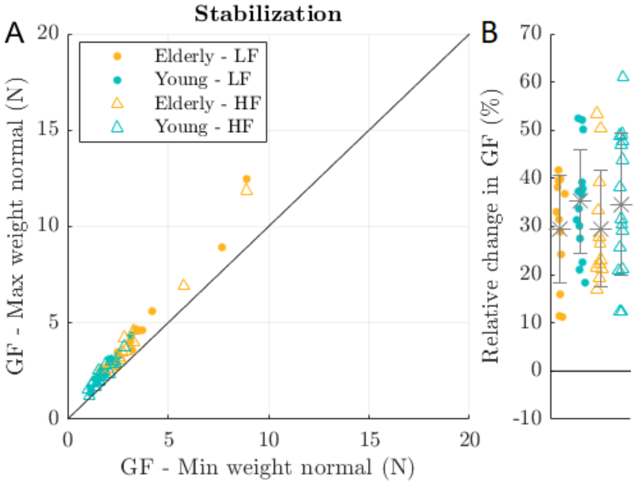


Figure 3.3.1: **A:** Mean value of GF during the static phase of normal trials for all participants ($n_{young}$ = 15, $n_{elderly}$ = 12). **B:** Difference in GF during the static phase of normal trials, relative to the mean value of the GF for the two weight conditions. Asterisks represent the average relative difference within each group and the grey lines represent the variance within each group. In panels A and B, one point/triangle corresponds to one participant. Orange markers are for elderly subjects while blue ones are for young participants. Dots represent normal trials under low friction (LF) (min weight: n=16, max weight: n=20) while triangles are for normal trials under high friction (HF) (min weight: n=17, max weight: n=18).

### 3.3.2 Weight catch trials

Second, we evaluated if there was already a change in GF behaviour during the static phase of weight catch trials. For this purpose, the GF during the static phase of weight catch trials was compared to the one of normal trials, associated with a different manipulandum weight. There were two types of weight catch trials:

1. *Minimal weight catch trial*: when previous trials were performed with the maximal manipulandum weight (i.e. 3.1 N).
2. *Maximal weight catch trial*: when previous trials were performed with the minimal manipulandum weight (i.e. 2 N).

In the case of minimal weight catch trials (Fig 3.3.2A-B), the object unexpectedly started to move. Indeed, subjects were accustomed to a higher weight and then, a greater force was needed before the object started to take off. During the static phase, we observed that all young participants decreased their GF in order to fit the minimum weight and not use unnecessary energy. A ∼20% decrease was observed. The friction did not influence this relative difference in GF between maximal and minimal weight (-22.0 and -22.53% under low and high friction respectively). It was a little bit less than for normal trials (∼-25%). However, not all older participants had adapted their GF to the weight condition. Indeed, under low friction, two participants did not decrease their GF while under high friction, one participant did not adapt. So, in total, three different participants did not adapt to minimal weight (but under different friction conditions). Mean curves of those participants were analysed and were made available in appendix D (Fig D.0.1, D.0.2). For those participants, we could observe that the GF became equivalent in the two conditions at the end of the static phase. For all elderly participants, the mean relative difference between the two conditions was -11.46% under low friction and -18.71% under high friction (instead of ∼-22% for normal trials).

In the case of maximal weight catch trials (Fig 3.3.2C-D), the object did not take off when participants thought it was going to be the case. The grip and load forces had to continue to increase until the force of gravity (3.1 N) was overcome. During the stabilisation phase, as the LF (equal to the weight) was higher, the GF had also to be higher than for minimal manipulandum weight condition. Again, we observed that all young participants exerted a higher GF for the maximal weight catch trials. The relative change in GF between the two conditions was ∼35%. This result was the same as the one obtained for normal trials. Then, they were perfectly adapted to weight at the stabilisation phase. Regarding elderly participants, they were all adapted under high friction. The relative change was about 28%. It was very close to the one obtained for normal trials (29.57%). However, under low friction, two participants did not adapt. Mean curves of those participants were analysed and available in appendix D (Fig D.0.3). It was important to note that one of those two participants was the same as one subject who was not adapted to minimal weight catch trial. Again, we observed that the curves overlapped at the end of the stabilisation phase. Under low friction, the mean relative change in GF was 23.51% for elderly participants. This was less than for normal trials but it seemed logical since two elderly participants did not adapt.

From those results, we concluded that the young group adapted very well to weight change and this already at the time of the static phase of the weight catch trials. For minimal weight catch trials, the decrease in GF was ∼22% (very close to normal trials, ∼25%) while for maximal weight catch trials, the GF change was ∼35%, which was the same result as the one obtained for normal trials. However, not all elderly participants adapted to weight change. In total, four participants did not adapt for the two conditions (i.e. minimal weight catch trials and maximal weight catch trials). However, the task was performed correctly. For maximal weight catch trial under high friction, the relative GF difference was very close to the one obtained for normal trials (∼30%).

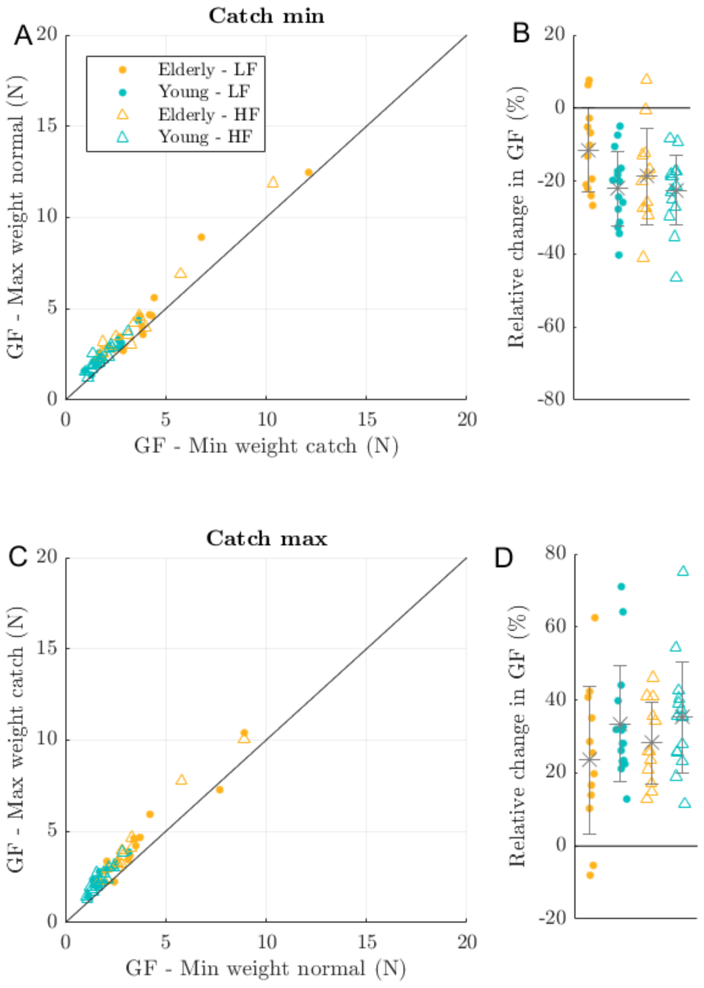


Figure 3.3.2: **A:** Mean value of GF for each glass during the static phase of minimum weight catch trials ($n_{LF}$=5 ,$n_{HF}$=4) and maximal weight normal trials ($n_{LF}$=20, $n_{HF}$=18) for all participants ($n_{young}$ = 15, $n_{elderly}$ = 12). **B:** Relative difference in GF between the mean GF during the static phase of minimal weight catch trials and maximal weight normal trials. **C, D:** Same as A, B except that the static phases of maximal weight catch trials ($n_{LF}$=4, $n_{HF}$=5) are compared to the static phases of minimal weight normal trials ($n_{LF}$=16, $n_{HF}$=17). In panels A, B, C and D one point/triangle corresponds to one participant. Orange markers are for elderly subjects while blue ones are for young participants. Dots represent trials with low friction glasses while triangles are for trials with high friction material. For B and D, asterisks represent the average relative difference within each group and the grey lines represent the standard deviation in each group.

### Time of the GF adjustment to weight

In the previous section, we observed that overall and for both age groups, the GF was adjusted to weight during the static phase of weight catch trials. Therefore, we investigated the temporal evolution of the GF during weight catch trials to determine the time at which the changes in GF occurred. We performed these analyses separately for the two age groups and compared the obtained results (Fig 3.3.4 and 3.3.5).

The kinematics of both age groups were very similar, as shown by the LF curves (Fig 3.3.4 and 3.3.5, top rows of each panel). During the static phase, we observed that the LF curves were different across conditions (i.e. maximal and minimal manipulandum weight). That was true for both age groups. For the minimal manipulandum weight, the LF was equal to 2 N while for the maximal weight, it was equal to 3.1 N. It was logical since during static phase, the LF was only equal to the weight of the manipulandum. During the dynamic phase, the LF curves were not as different as expected. This could be explained by the presence of the counterweight. Indeed, when the manipulandum weight decreased, the inertia increased since a mass was added on the counterweight. However, as we have seen, the load force is equal to the sum of the inertial force and the weight. Then, an increase in inertia could partly compensate the decrease in weight. We could also notice that in both cases (maximal and minimal manipulandum weight), gravity helped the participant to slow the object down. Indeed, the LF was never negative. Figure 3.3.3 showed that the highest $\Delta$LF occurred during the deceleration phase for both groups. This actually happened because, under minimal weight, the deceleration of the manipulandum was more difficult, due to the presence of the heavier counterweight. This figure showed also that $\Delta$LF was similar between the two age groups.

For the minimal weight catch trials under low friction (Fig 3.3.4A-B), we found that the GF difference for young participants reached statistical significance (GMLE, $p < 0.001$) 230 ms after the time that participants could realize that the manipulandum weight had changed (LF=2 N) (Fig 3.3.4A). The difference at that time was -7.44%. However, for elderly participants, the difference between conditions never reached statistical significance (Fig 3.3.4B). It could be explained by the important standard deviation across subjects. Moreover, in this condition, two elderly participants did not adapt until the end of the static phase. By the way, we could observe that the p-value decreased during the static phase. For the two age groups, we could observe that the GF difference was the largest during the static phase. However, the highest difference in LF was during the deceleration.

For the minimal weight catch trials under high friction (Fig 3.3.4A-B), the GF difference reached statistical significance for the two age groups (140 ms and 210 ms after the moment at which participants could realize that the weight changed, for young and elderly participants respectively). For young participants, it was earlier than under low friction. Elderly participants seemed to adapt later than the young ones. In that condition, one elderly participant did not adapt to minimal weight during the static phase. The GF difference at those times was 8.79% and 20% for young and elderly participants respectively. The high difference was logical since the significant GF difference appeared much later for the elderly group. Again, for both groups, the difference in GF was the highest at the end of the static phase.

For the maximal weight catch trials under low friction (Fig 3.3.5A-B) the GF difference reached statistical significance in both age groups. For young participants, 150 ms after the moment at which participants could realize that the weight changed and for elderly, at 1.32 s, during the static phase. In this condition, two elderly participants did not adapt to the maximal weight during the static phase. The GF difference at those times was 10% and 21.31% for young and elderly participants respectively.

For the maximal weight catch trials under high friction (Fig 3.3.5C-D), the GF difference also reached statistical significance in both age groups. For young participants, 170 ms after the moment at which participants could realize that the weight changed and for elderly, at 830 ms, during the static phase but earlier than under low friction condition. The GF difference at those times was 8.24% and 23.19% for young and elderly participants respectively.

From those results, we concluded that overall, young participants adapted to the weight conditions during the lifting of the object. The average time at which the difference in GF was statistically significant was 0.155 seconds after the first moment at which they were able to perceive that the weight was not the same as in the previous trial. Then, the adaptation was very fast. For elderly participants, we observed that the shape of the ΔGF curves was very similar to the one of the young group (Fig 3.3.6). However, significant difference between the two conditions was only found later. Indeed, it appeared during the static phase for maximal weight catch trials and after the acceleration phase for the minimal weight catch trials under low friction. From figure 3.3.6, we also observed that young participants always had a higher difference in GF than elderly participants. Moreover, the ΔGF did not seem to be impacted by the friction condition. However, for elderly participants, ΔGF was more important under high friction than under low friction.

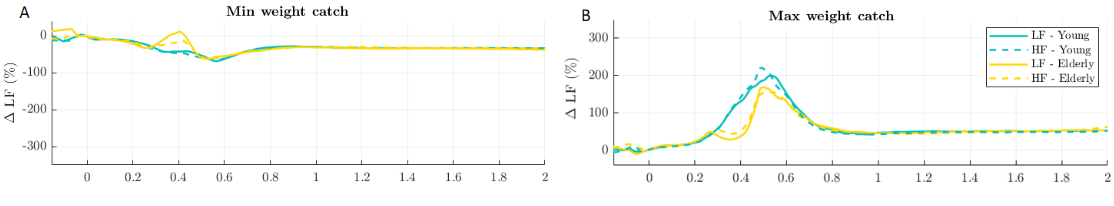


Figure 3.3.3: **A:** Evolution of LF difference (catch-normal) as function of time for the first movement of minimal weight catch trials under low friction (LF) (n=5) and high friction (HF) (n=4) for all participants of each group ($n_{young}$=15, $n_{elderly}$=12). Lines are averages across participants. Orange represents elderly participants and blue is for young participants. Continuous traces are trials under low friction and dashed lines are trials under high friction. **B**: Same as A but for maximal weight catch trials under LF (n=4) and HF (n=5).

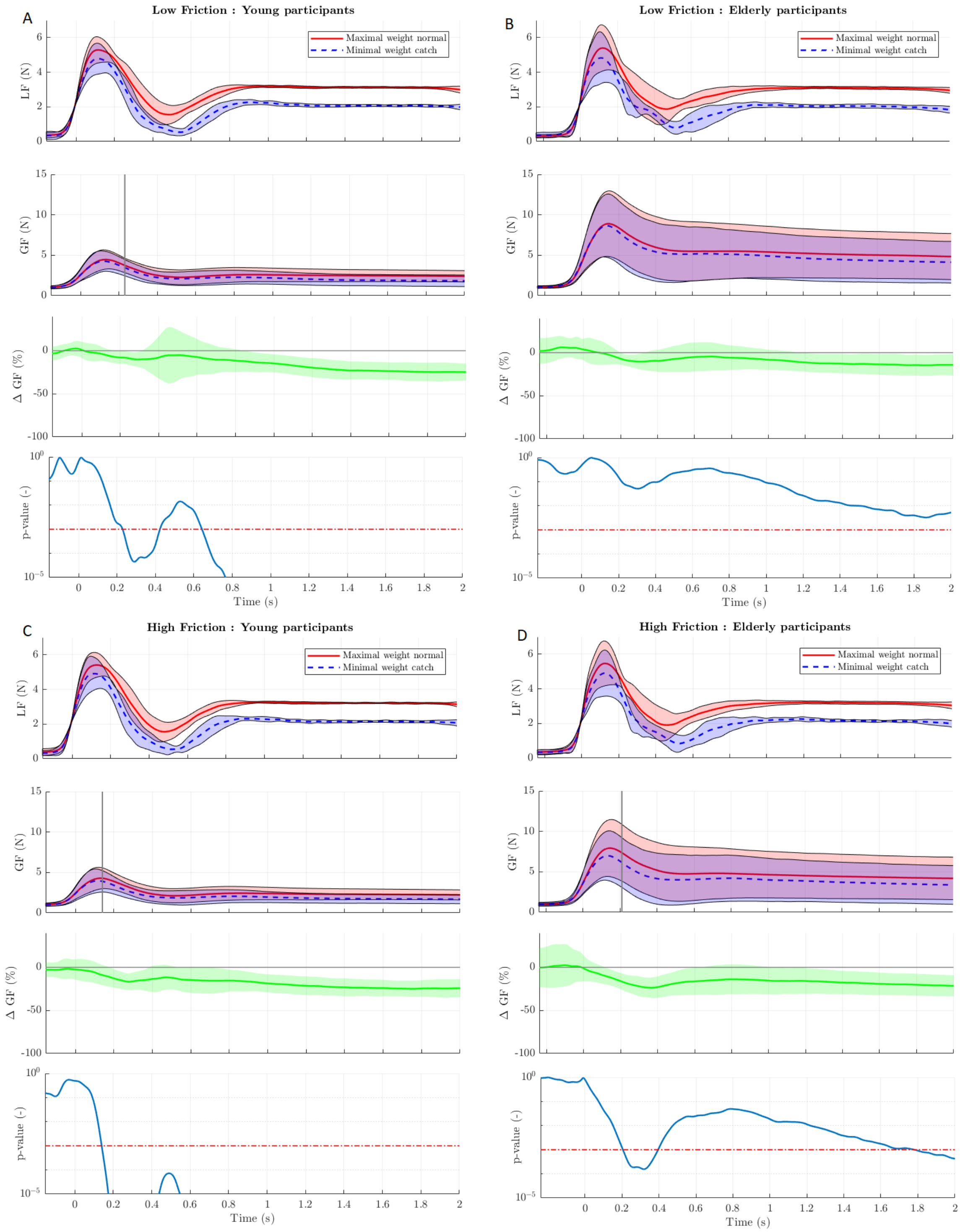


Figure 3.3.4: **A:** Evolution of LF, GF, GF difference and p-value as a function of time for the first movement of minimal weight catch trials under low friction (n=5) for all young participants (n=15). Trials are synchronized at the moment when the LF is equal to 2 N (i.e. minimal weight of the manipulandum). 0 second correspond to that point. Lines are averages across participants and shaded areas are the standard deviation. Red is for maximal weight and blue is for minimal weight. Continuous traces are normal trials and dashed lines are weight catch trials. The grey line shows the time of the statistically significant difference between GF curves (GLME, $p$<0.001). The third panel shows weight catch minus normal trials. The red dash-dotted line in the lower panel shows the threshold below which the difference is significant. **B:** Same as A for elderly participants (n=12). **C:** Same as A for minimal weight catch under high friction (n=4). **D:** Same as C for elderly participants.

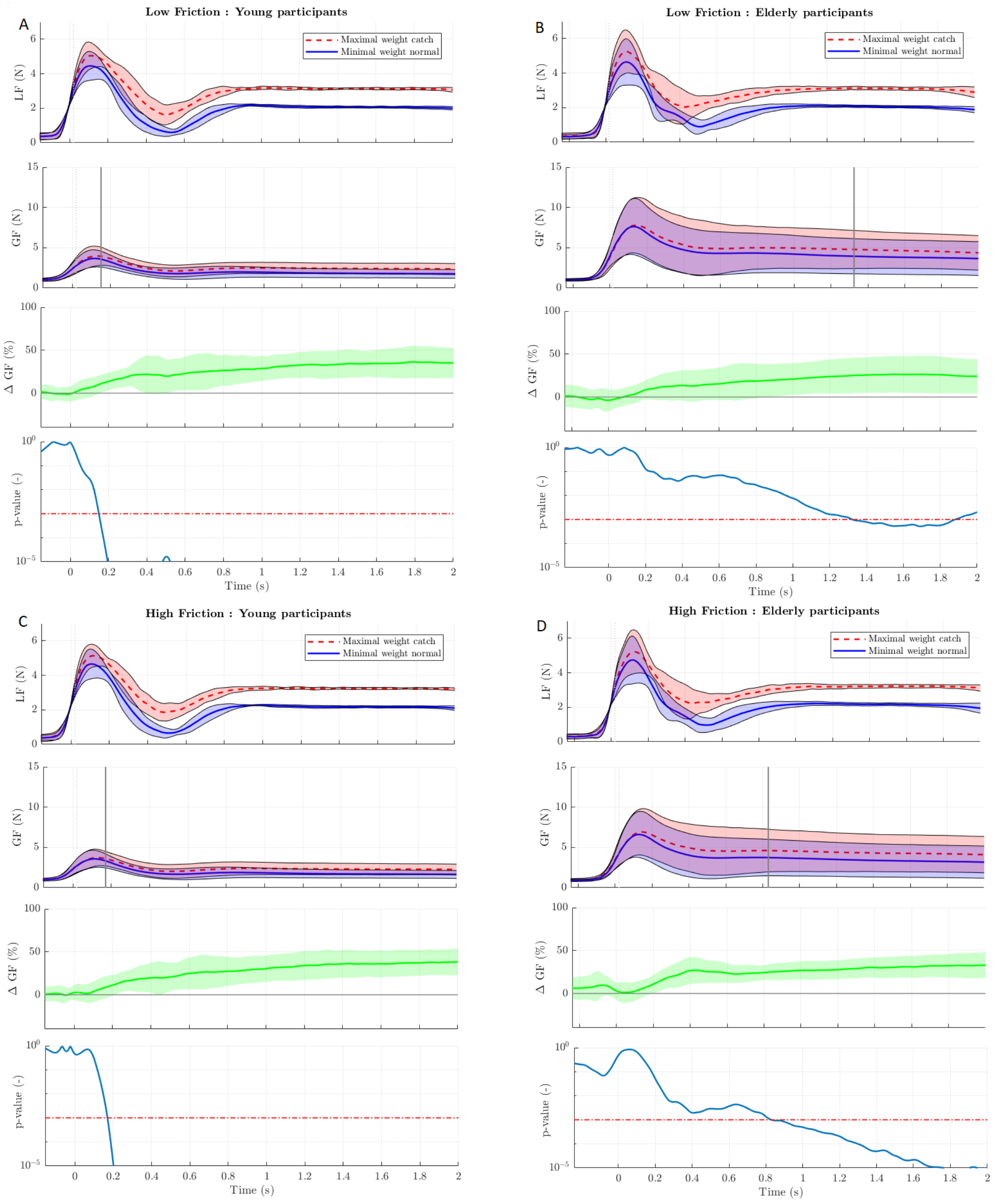


Figure 3.3.5: **A:** Evolution of LF, GF, GF difference and p-value as a function of time for the first movement of maximal weight catch trials under low friction (n=4) for all young participants (n=15). Trials are synchronized at the moment when the LF is equal to 2 N (i.e. minimal weight of the manipulandum). 0 second correspond to that point. Lines are averages across participants and shaded areas are the standard deviation. Red is for maximal weight and blue is for minimal weight. Continuous traces are normal trials and dashed lines are weight catch trials. The grey line shows the time of the statistically significant difference between GF curves (GLME, $p<0.001$). The grey dotted line represents the moment at which the LF is equal to 3.1 N (maximal manipulandum weight). The third panel shows weight catch minus normal trials. The red dash-dotted line in the lower panel shows the threshold below which the difference is significant. **B:** Same as A for elderly participants (n=12). **C:** Same as A for maximal weight catch under high friction (n=5). **D:** Same as C for elderly participants.

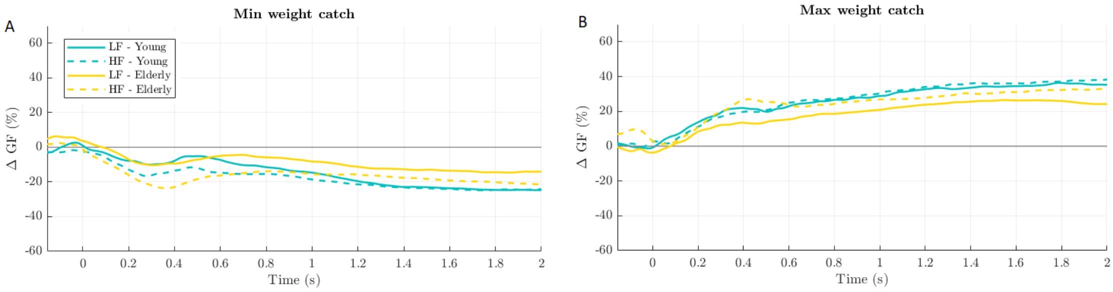


Figure 3.3.6: **A:** Evolution of GF difference (catch-normal) as a function of time for the first movement of minimal weight catch trials under low and high friction for all young participants (n=15) and all elderly participants (n=12). Trials are synchronized with the moment during which the LF is equal to 2 N (i.e. minimal weight of the manipulandum). 0 second correspond to that point. Lines are averages across participants. Orange curves are for elderly participants while blue curves are for young subjects. Continuous traces represent trials under low friction and dashed lines represent trials under high friction. **B:** Same as A but for maximal weight catch trials.

| | | | **Young** | **Elderly** |
|---|---|---|---|---|
| Normal trials | LF | GF difference (%) | 35.09[1]or -25.6[2] | 29.36 or -22.13 |
| | HF | | 34.57 or -24.87 | 29.57 or -22.24 |
| Minimal weight catch | LF | GF difference (%) | -22.00 | -11.46 |
| | HF | | -22.53 | -18.71 |
| Maximal weight catch | LF | | 33.25 | 23.51 |
| | HF | | 35.12 | 28.23 |
| Minimal weight catch | LF | Time (s) | 0.23 | - |
| | | GF difference (%) | -7.44 | - |
| | HF | Time (s) | 0.14 | 0.21 |
| | | GF difference (%) | -8.79 | -16.43 |
| Maximal weight catch | LF | Time (s) | 0.15 | 1.32 |
| | | GF difference (%) | 10.10 | 21.32 |
| | HF | Time (s) | 0.17 | 0.83 |
| | | GF difference (%) | 8.24 | 23.19 |

Table 3.2: Comparison young/elderly - Adaptation to weight. The time taken up has as reference the moment at which the participants could realize that the weight of the manipulandum changed. [1] if mean GF during min weight trials is taken as reference, [2] if mean GF during max weight trials is taken as reference. For minimal weight catch, max weight is taken as reference while for maximal weight catch, min weight is taken as reference.

### Images analysis

In order to evaluate if the deformation of the fingerprint gave information to the subject about the GF to apply, the strain rate norm was computed for the different weight conditions. The LF curves visible in figures 3.3.7 and 3.3.8 were plotted only with participants whose images were analyzed ($n_{young}$=10, $n_{elderly}$=8).

For minimal weight catch trials (Fig 3.3.7), the strain rate norm curves were lower than those of maximal weight normal trials during the acceleration phase. It was the case in both groups. During the deceleration phase, it was the reverse situation. For young participants (Fig 3.3.7A-C), the signifiant change between the curves appeared during the acceleration phase under the two conditions (low and high friction). It was before the significant change in GF (0.0783 vs 0.23 s under low friction and 0.0783 vs 0.14 s under high friction). In the two cases, the difference was ∼-22%. For elderly participants (Fig 3.3.7B-D), the strain norm curves reached only significant difference under low friction at 0.35 s (63.95%), during the deceleration phase. However, in the GF curves, no significant difference appeared between the two conditions.

For maximal weight catch trials (Fig 3.3.8), we could observe that for the two age groups, the strain rate norm was higher for maximal weight catch trials than for minimal weight normal trials during the acceleration phase. Then, it was the same observation than in the previous strain rate norm analysis (i.e. minimal weight catch trials and maximal weight normal). During the deceleration phase, the strain rate norm curve of minimal weight normal trials was slightly above the one of maximal weight catch trials. For young participants (Fig 3.3.8A-C), the time at which the strain rate curves were significatively different was 1.11 and 0.0783 s under low and high friction respectively. The difference was about 23% in both cases. For elderly participants (Fig 3.3.8B-D), no significant difference in strain rate norm was found under low friction. However, under high friction, the time of significant divergence was 0.057 s and the difference was 41%.

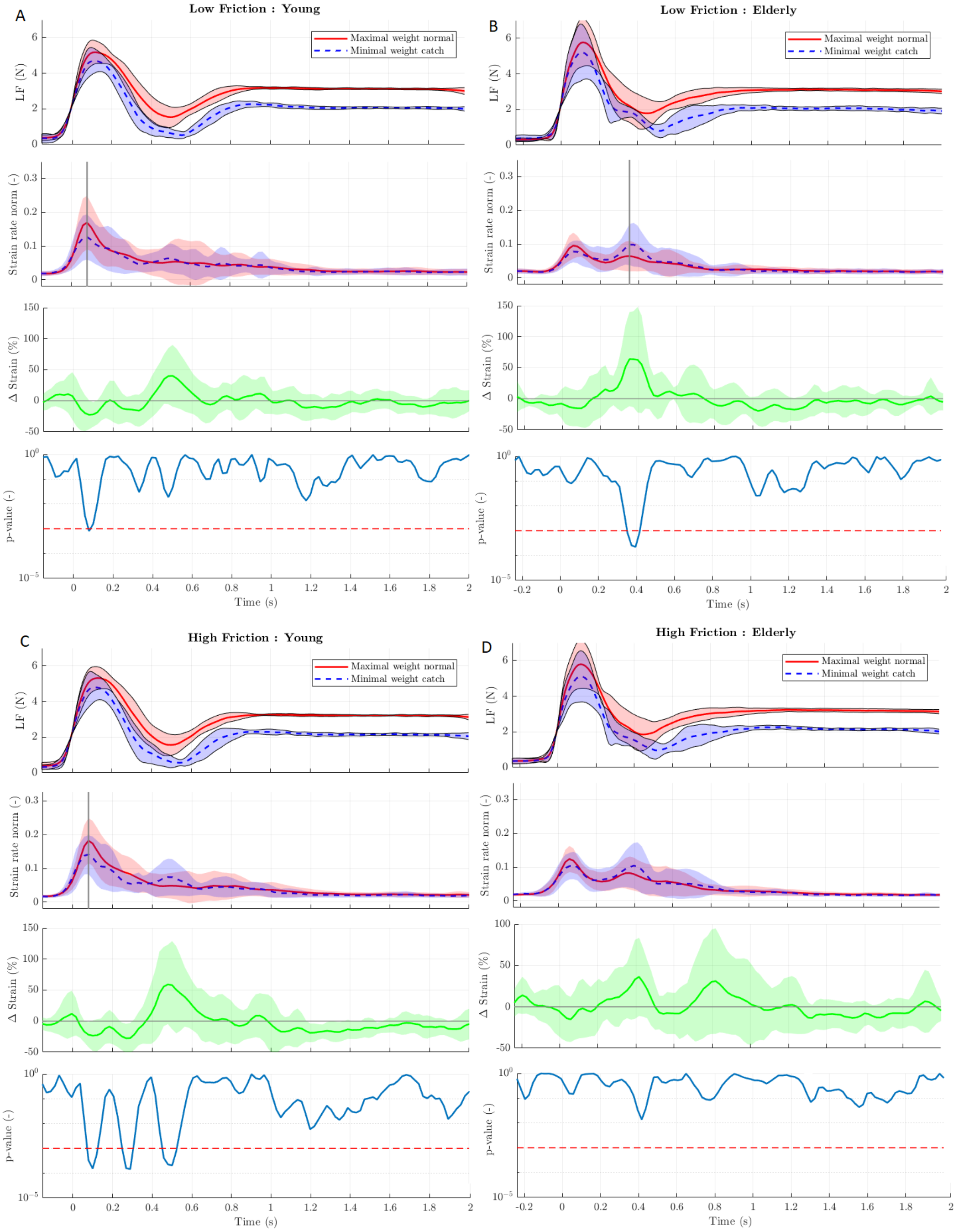


Figure 3.3.7: **A:** Evolution of LF, strain rate norm, strain rate norm difference and p-value as a function of time for the first movement of minimal weight catch trials under low friction (n=5) for all young participants who had analyzable images (n=12). Trials are synchronized at the moment when the LF is equal to 2 N (i.e. minimal weight of the manipulandum). 0 second corresponds to that point. Lines are averages across participants and shaded areas are the standard deviation across subjects. Red is for maximal weight and blue is for minimal weight. Continuous traces are normal trials and dashed lines are weight catch trials. The grey line shows the time of the statistically significant difference between GF curves (GLME, $p<0.001$). The third panel shows weight catch minus normal trials. The red dash-dotted line in the lower panel shows the threshold below which the difference is significant. **B:** Same as A for elderly participants who had analyzable images (n=8). **C:** Same as A for minimal weight catch under high friction (n=4). **D:** Same as C for elderly participants.

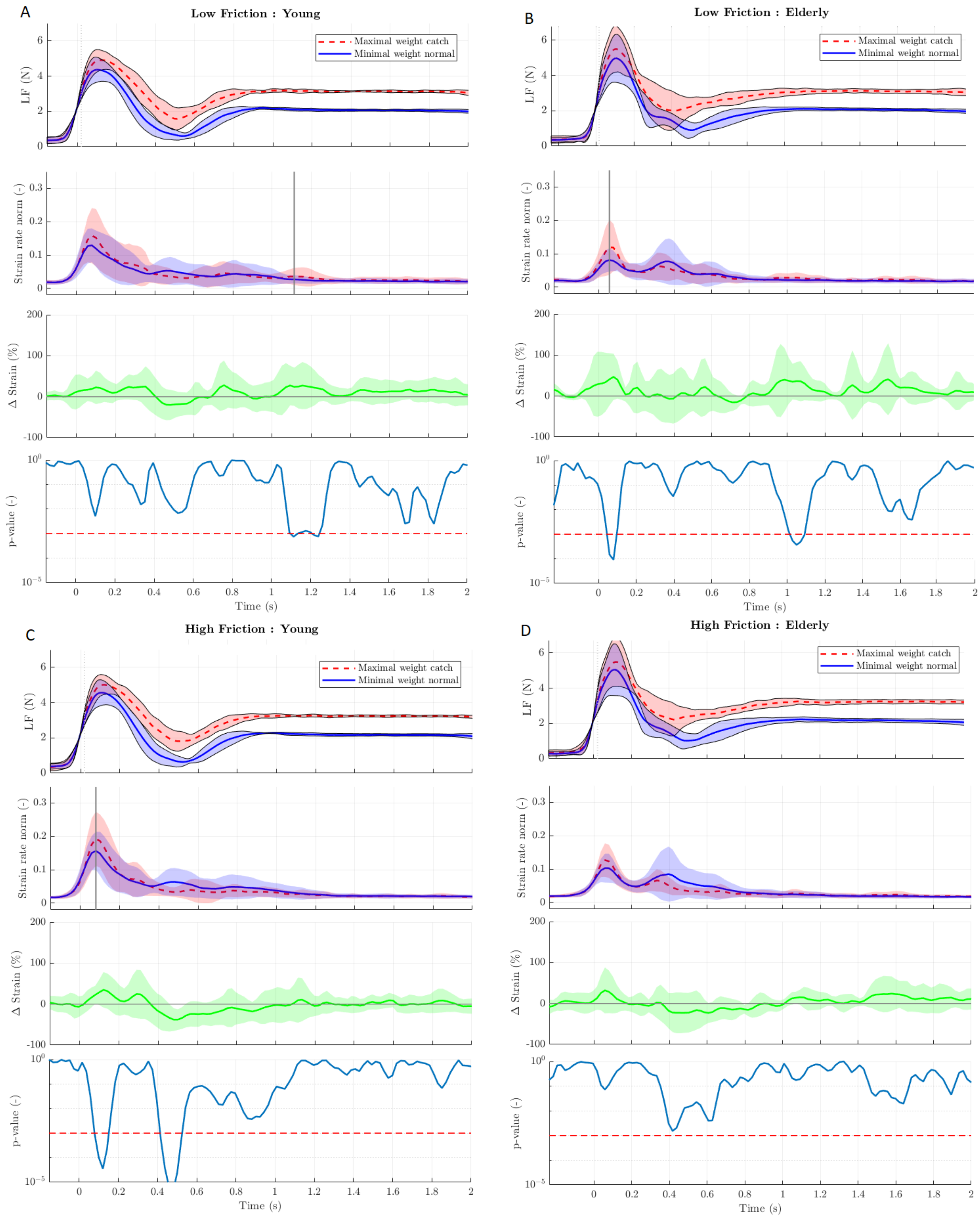


Figure 3.3.8: **A:** Evolution of LF, strain rate norm, strain rate norm difference and p-value as a function of time for the first movement of maximal weight catch trials under low friction (n=4) for young participants who had analyzable images (n=12). Trials are synchronized at the moment when the LF is equal to 2 N (i.e. minimal weight of the manipulandum). 0 second corresponds to that point. Lines are averages across participants and shaded areas are the standard deviation across subjects. Red is for maximal weight and blue is for minimal weight. Continuous traces are normal trials and dashed lines are weight catch trials. The grey line shows the time of the statistically significant difference between strain rate norm curves (GLME, $p<0.001$). The grey dotted line represents the moment at which the LF is equal to 3.1 N (maximal manipulandum weight). The third panel shows weight catch minus normal trials. The red dash-dotted line in the lower panel shows the threshold below which the difference is significant. **B:** Same as A for elderly participants who had analyzable images (n=8). **C:** Same as A for maximal weight catch under high friction (n=5). **D:** Same as C for elderly participants.

## 3.4 GF/LF ratio

For all participants, we looked at the normal to tangential force ratio (GF/LF) (Fig 3.4.1). The analysis was performed for the static phase of normal trials. First, we could observed that the GF/LF ratio was higher for elderly participants than for young ones. It made sense since, theoritically, this ratio fits the frictional condition (GF/LF inversely proportional to the friction coefficient) and we observed that elderly subjects had lower friction coefficients. Second, as it was observed in previous analyses, there was more variance within the elderly group. Third, by comparing the weight conditions under same friction condition (min LF with max LF and min HF with max HF), we could observe that the ratio was higher under minimal weight, especially for elderly participants. For young participants, the normal to tangential force ratio seemed to be closer between conditions, except for trials under high friction and maximal weight. It was the lowest in this condition. Last, we noticed that two of the older participants with the highest GF/LF ratio (gray and purple dots) were those who did not adapt to the maximal weight during maximal weight catch trials. Their safety margins seemed to be higher during minimal manipulandum weight trials.

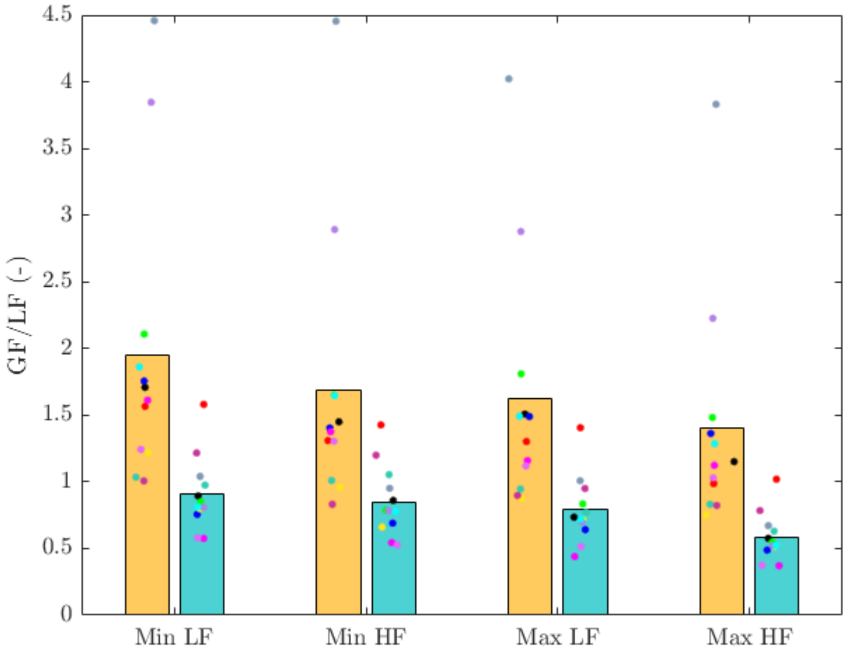
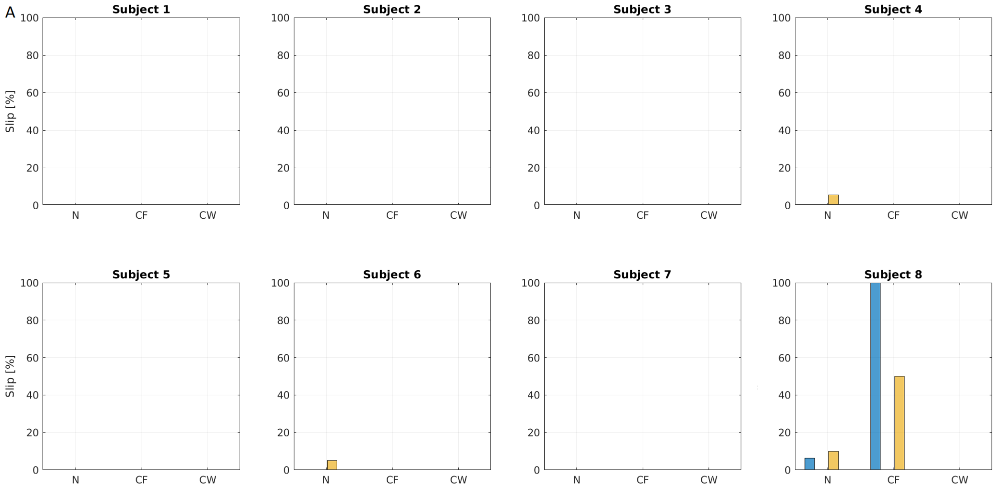


Figure 3.4.1: GF/LF ratio of all participants computed by dividing the mean GF during the static phase by the weight of the manipulandum (i.e 2 or 3.1 N). Yellow bars are for elderly participants while blue ones are for young subjects. For each group, a dot of the same color corresponds to the same participant across conditions.

## 3.5 Slip trials

In order to compare the proportion of full slip trials between the two groups, we computed the proportion of trials per participant for which a full slip occurred during the lifting of the manipulandum (Fig 3.5.1). It appeared that, most of elderly participants did not performed full slips trials (i.e. first percentile of feature displacements above 0.1 mm). Two elderly subjects had few (∼5%) full slip trials for normal trials under maximal weight and low friction. One elderly participant had full slip trials in four different conditions. However, each time, it was under low friction and maximal weight (for normal and low friction catch trials). It seemed logical that majority of full slip trials occurred in those conditions because they were risky, especially the low friction catch trial under maximal weight. Indeed, the surface was more slippery, leading to an increase risk of the object falling. However, for young participants, we observed that most experienced full slip trials. Only two of the thirteen participants did not experience any. In most cases (5/11), the condition for which the percentage of full slip trials was the highest was low friction catch under maximal weight. Again, that was logical since low friction led to more slippery surface and maximal force requiered a higher level of force.

We also looked at the mean displacements of the features points (Fig 3.5.2). We observed that the displacement values were not of the same order of magnitude between the two age groups. It was however important to remain careful because all subfigures were not at the same scale for visibility reason. We could observe that in average, the mean displacement is in the micrometer range for the majority of elderly participants. For young subjects, it was of the order of the $10^{-2}$ mm. Therefore, we could conclude that there were more slips within the contact area of young participants.



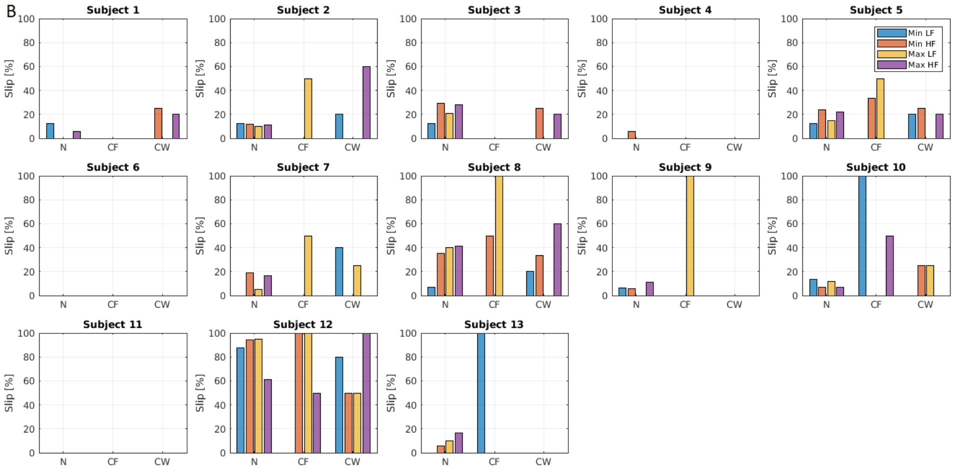


Figure 3.5.1: **A:** Percentage of full slip trials calculated on the basis of the first percentile of feature points total displacement, for each condition and each elderly participants who had analyzable images (n=8). "N" represents normal trials, "CF" represents catch friction trials and "CW" is for catch weight trials. Blue is for minimal weight under low friction trials, orange for minimal weight under high friction trials, yellow represents maximal weight under low friction trials and purple is for maximal weight under high friction trials. **B:** Same as A for young participants who had analyzable images (n=13).

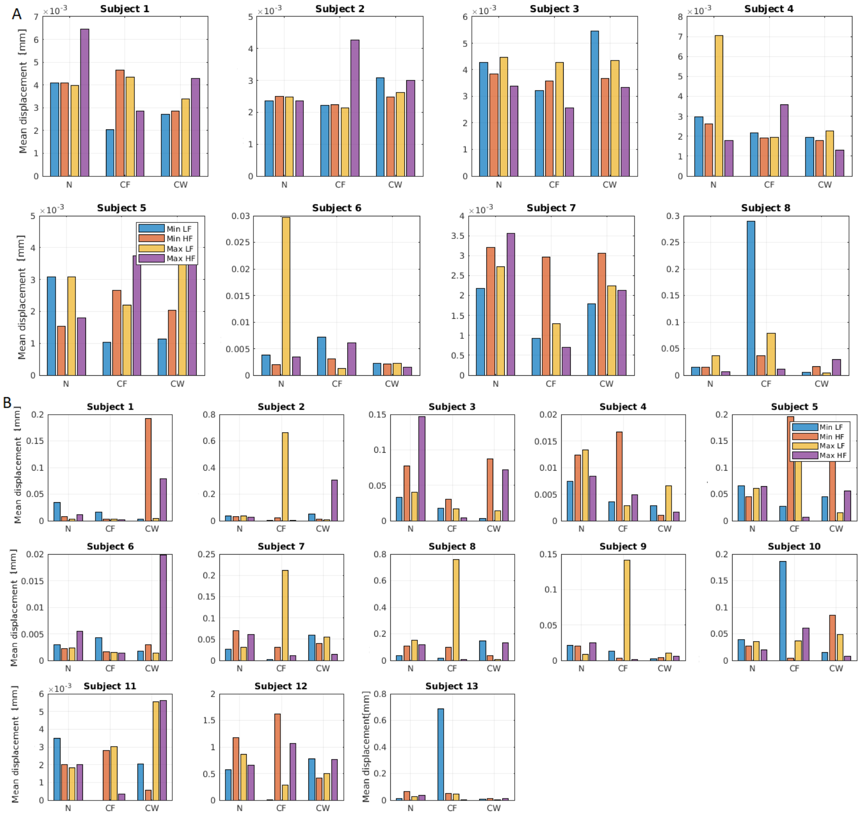


Figure 3.5.2: **A:** Mean displacement of features points per condition and for each elderly participants who had analyzable images (n=8). "N" represents normal trials, "CF" represents catch friction trials and "CW" is for catch weight trials. Blue is for minimal weight under low friction trials, orange for minimal weight under high friction trials, yellow represents maximal weight under low friction trials and purple is for maximal weight under high friction trials. **B:** Same as A for young participants who had analyzable images (n=13).

# Chapter 4

# Discussion

## Main results and comparison with the literature

### Kinematics and forces applied

*Higher GF exerted by older participants and higher variance within older group*

Overall, both young and elderly subjects had an equivalent kinematics. However, the level of GF applied was significantly different between the two age groups. Indeed, elderly participants exerted higher grip forces than young subjects. Moreover, the standard deviation was also greater within the elderly group. Those results matched the results obtained by K.J Cole [12]. Indeed, they observed a higher GF for elderly participants as well as greater variance within and between subjects. During the experiment, we also noticed that sometimes, elderly participants took more time to perform the lift of the manipulandum. They were also less reactive than young people.

### Friction

*Smaller coefficients of friction in older people*

The average static friction coefficients of elderly participants were smaller than those of young participants. This could be due to the changing skin properties linked to aging. Indeed, skin hydration decreases with age, which leads to a decrease of the contact area [4] and then a decrease in friction coefficient [6, 36]. Other skin changes could also lead to a decrease in the coefficient of friction. Indeed, accelerated degradation and decreased syntheses of collagen and elastin by elderly people lead to reduced cutaneous elasticity [4]. K.J. Cole had also observed this decrease in friction coefficient for elderly participants [12]. Another study also showed that there was a negative correlation between coefficient of friction and aging [49]. Nevertheless, it was also reported that, due to menopause, women may have drier skin due to the loss of estrogens [2, 3]. However, it was not necessarily the women who had the lowest friction coefficients in this study. Another observation in that part was the fact that the relative difference between the two friction coefficients was higher for elderly participants ($\sim$43%) than for younger ones ($\sim$15%). In the study of F. Schiltz [14] which was carried out with the same set of glasses, the average relative difference in friction was 23%. This result seemed relatively close to the one we obtained for the young group.

*Normal trials: Higher GF under low friction for both groups, higher relative difference in GF in older adults*

For normal trials, both groups exerted more GF under low friction, even though the level of GF varied widely across participants, especially for the older group. It was the case whatever the weight of the manipulandum. Those results were consistent with those of F. Schiltz et al. [14]. The average relative difference in GF was higher for elderly participants (∼16%) than for young ones (∼ 8.5%). It seemed logical since the average relative difference in friction was higher for elderly subjects. However, in both cases, the relative difference in GF was not of the same order of magnitude as the relative friction difference. In the study of F.Schiltz, the two differences were relatively close to each other (23% relative difference in friction while 15% GF relative difference during normal trials).

*Low friction catch trials: relative difference in GF of the same order of magnitude than relative difference in coefficients of friction for both groups*

For low friction catch trials, both groups seemed to be adapted during the static phase. This condition required a higher GF since the surface was more slippery than during previous trials. On average, the relative change in GF was ∼42% for elderly participants and ∼15% for younger ones. These relative changes were of the same order of magnitude that the relative difference in friction in both groups. The same result was observed in the study of F.Schiltz [14]. However, we noted than some participants did not exert more GF during those trials. Therefore, we assumed that the GF applied during high friction normal trials was higher than needed. Another possibility was that, although the difference in friction was determined to be greater than 10%, this was not the case throughout the experiment. Therefore, no adapation to friction was required. About the time of the signicant GF difference between conditions, results were not as significant as those of F.Schiltz et al. [14]. Indeed, they found that participants adapted their GF 370 ms after contact with surface. In this study, for young participants, significant GF difference was only found under maximal weight (383 ms after the sound indicating to lift the object). This result was very close from the one observed in the F.Schiltz study. However, in this experiment, subjects were in contact with the manipulandum before the beginning of the lift. For elderly participants, significant GF difference appeared later (between 500 and 600 ms after the sound indicating to lift the object). It could be due to the tactile sensibility impairment linked to aging [12, 41, 42].

*High friction catch trials: For both groups, no consistent results obtained, no adaptation seemed to take place*

For high friction catch trials, results were less consistent in both groups. It could be explained by the fact that there was no emergency to adapt since the risk of slip was reduced. Nevertheless, in their study, F.Schiltz et al. [14] showed that there was a decrease in GF level during high friction catch trials, although this change occurred later than for low friction catch trials. However, their study was more robust since they had more friction catch trials (5 low friction catch trials and 5 high friction catch trials).

*Strain rate norm curves: strain rate norm curve of low friction catch trials higher than the one of high friction normal trials for both groups.*

With the images analyses, we showed that, except for the young group under minimal weight, the strain rate norm curves of the low friction catch trials were higher than those of high friction normal trials. Then, the difference in skin strain could constitute a warning signal to the CNS to adjust the GF. However, the concordance in time (between the time of significant difference in strain and the one of GF) was not very consistent except for low friction catch trials under minimal weight, for the elderly group. The significant change in strain rate norm curve appeared before the significant change in GF. However, the minimal interval of time needed for the sensory feedback to reach the CNS and trigger a motor response is 90 ms [14], which is more that we observed in that case (5 ms). F.Schiltz et al. [14] showed that significant increase in skin deformation arised over 100 ms before the motor response.

In some studies [41, 42], it was reported that the size, the density and the complexity of some mechanoreceptors decline significantly with aging. It was also observed that vibrotactile detection thresholds and minimum detectable levels of vibration increase with age [4]. Thus, it means that elderly participants could be less sensitive to skin deformation than young ones [12]. Moreover, normally, the bulk dynamics of deformation are slower with moist skin. Then, it is easier for the CNS to sense partial slips and correct the action [6]. However, as seen just before, elderly participants seemed to have a dryer skin. Despite all these elements, we saw that they adapted to the low friction condition. Then, it appeared that they were able to receive information from mechanoreceptors to properly adapt to the low friction condition. However, given the high relative friction difference, it was an emergency for them to increase their GF level.

*Those results should be taken with caution*

The results concerning this part must be taken with precaution. Indeed, only few friction catch trials have been taken into account (less than five - 1, 2 or 3). It was due to the large number of possible combinations (weight-friction). Besides this, friction catch trials were the first of the blocks, which could lead to a bias since there was a pause time just before. Therefore, the fact that high friction catch trials GF curves were above the ones of low friction normal trials GF curves could also be due to the effect of the first trial.

### Weight

*Normal trials: participants within each group exerted a higher GF for maximal manipulandum weight. The relative difference in GF between the two conditions was a little bit lower in the older group*

For normal trials, all participants within each group adapted to weight. The relative change in GF was slightly higher for young than for elderly participants (∼35% vs ∼30%) and not influenced by the friction condition.

*Weight catch trials: not all elderly subjects adapted to weight while all young did*

For the weight catch trials, during the static phase, young participants were all adapted in both conditions (i.e. minimal and maximal weight catch trials). However, it was not the case for elderly participants. In total, four participants did not adapt to the weight condition. For minimal weight catch trials, there was no emergency but for maximal weight catch trials, as the load force was higher during the static phase, it was necessary to increase the level of GF. Then, it meant that those participants exerted a higher GF than necessary during minimal weight trials and the latter was sufficient to counteract the maximal weight. We could then identify two strategies: young group always minimized the energy spent while some participants of the elderly group applied more force than needed and did not take any risks (more cautious strategy). This observation was also made in the study of K.J. Cole [12].

*Elderly subjects took more time to adapt to the weight condition and the $\Delta GF$ was lower under low friction*

For young subjects, the mean time to adapt to weight was about ∼155 ms after the first time they could realize that the weight of the manipulandum was not the same as during the previous trials. For minimal weight catch trials under high friction, it was at 210 ms for elderly participants. However, significant difference for maximal weight catch trials occurred during the stabilization phase. It could be explained by the large standard deviation inside this group. Normally, the proprioceptive feedback has a delay of 50 to 60 ms [50]. However, it was reported that older people may have an impaired proprioceptive function, which might explain the latter adaptation [23, 7]. Moreover, several studies reported the fact that older participants relied more on internal models than on sensory feedback and that they were slower to adapt to changes [9, 10, 11]. Johansson et al. [15] showed that during lifting series with unexpected weight changes, the force rate profiles were programmed on the basis of the previous weight and therefore, on the basis of predictions. Thus, if elderly participants relied more on internal models and had a proprioceptive function altered, it could lead to later adaptation. We also noticed that the GF difference between conditions (catch and normal) was lower under low friction than under high friction. For young participants, those differences were the same. Then, elderly participants seemed to be more cautious under low friction.

*Strain rate norm curves: Difficult interpretation in the case of weight changes*

The analysis of the strain rate norms for weight catch trials were more difficult to interpret. During the acceleration phase it seemed that the strain rate norm was higher under maximal manipulandum weight trials than for minimal weight trials, in both groups. It could be explained by the fact that the safety margin under minimal weight was higher and then led to less partial slips.

### GF/LF ratio

*Higher GF/LF ratio for elderly participants and higher safety margin under minimal manipulandum weight for older subjects*

The GF/LF ratio was higher in the elderly group than in the young one. It made sense since it was inversely proportionel to the friction coefficient. We observed that the older subjects had a higher GF/LF ratio under minimal weight, independently of the friction coefficient. Therefore, it confirmed the fact that some elderly participants exerted more force than needed during minimal weight trials. Thus, for those participants, it was not an emergency to increase the level of GF for maximal weight catch trials. Indeed, their safety margin was sufficiently high to counteract the maximal manipulandum weight. This was even more consistent considering that the two with the highest GF/LF ratio were the participants who had not adapted to the maximum weight catch trials. The ratio was higher under minimal than under maximal weight. It was consistent with the study of K.J. Cole [12] who noticed that elderly participants had a larger safety margin while manipulating objects. He explained that it could be due to a strategic response to tactile sensibility impairment. For young participants, the normal to tangential force ratio seemed to be closer between conditions. The lower ratio could be explained by the higher friction coefficient.

### Finger pad strains and slips

*Less strain rates in elderly subjects. It could be due to the excess of GF that led to less partial slips but also to anatomical changes of the skin*

The strain rate norms of young participants were always higher than the ones of elderly subjects. The explanation could be that older subjects exerted a higher GF than needed, leading to less partial slips and then, less strains. Moreover, the skin being less elastic, it deformed less. Therefore, they acquired less tactile information. We also noticed than in elderly participants, there were two peaks, linked to the acceleration and deceleration phases. For young participants, it was less marked. Only the peak due to the acceleration phase was clearly visible.

*Less full slips trials in elderly participants as well as less displacements of features points*

With the images, we also observed that the percentage of full slip trials was higher for young participants than for elderly. In both groups, the condition that led to the highest percentage of full slip was under low friction. That made sense, since the surface was more slippery. Another observation was that the mean total displacement of feature points was lower in all conditions that the one of young subjects. Those two observations could again be due to the fact that the older subjects exerted more force than needed. On the contrary, young participants exerted less force, leading to more diplacements of feature points.

# Limitations

### Experimental protocol and manipulandum

The total time of the experiment was two hours. It was long but required a large sample of data. Indeed, as the friction and the weight were changed, many combinations had to be tested. We noticed that, at certain moments, participants were less focused on the task and the movement performed was not always exactly the same. This was understandable since the action had to be performed 120 times. However, it could bring variance in the results as well as bias. Besides this, there was a pause time between each block to enable experimenters to interchange the glasses in order to vary the friction. This break cut the participant off from the task, so the following trial could be slightly biased.

It is also important to underline that, given the many parameters, the amount of trials in some conditions was very few (less than five trials). This was especially the case for friction catch trials. Therefore, the random factor was present and must be taken into account. Moreover, friction catch trials were always the first trial of a block. Then, it was preceded by a pause time. The effect of the first trial could therefore be present and could explain a higher GF level during those trials.

About the manipulandum used, there were also some limitations. Indeed, the real mass of the manipulandum was 540 g but the weight was in part compensated by a counterweight. However, it modified the weight/inertia relationship and therefore made handling less natural [43]. Moreover, the apparent weight was lower than the one expected from the appearence [43]. Then, visual system that provides key information about the size and the distribution of weight of the object may have sent inputs that tended to increase the GF [18, 43]. A last limitation about the set-up was the contact surface (glass). The latter was different from the one of most natural objects [43] and led to less spontaneous handling.

### Size of the sample

As mentioned, the young group was composed of 15 participants while the older one was constituted of 13 subjects. However, one elderly had to be excluded due to the wrong kinematics. It would have been statistically more relevant to have a larger number of subjects in order to have more robust results (especially for elderly participants for which the standard deviation between subjects was very important). Nevertheless, given the duration of the experiment, it was difficult to perform the experiment with more subjects in the context of this master thesis.

### Computation of the mean coefficient of friction

The friction coefficient between the manipulandum and the fingers was characterized by a constant scalar value per partipant-glass pair. This was clearly a very large approximation. Indeed, the characteristics of the skin changed over time, therefore over the course of the trial. This is normally due to the presence of sweat pores on the surface of the skin which produce moisture at the interface. This characteristic affected the level of friction within a trial because of the occlusion phenomenon. The latter was very present in the experiment as the participants were in contact with the glass before starting the lift (at least for ∼four seconds, at most for 10 seconds). Moreover, the experiment lasted two hours, so the properties of the skin were certainly not the same throughout the experiment. It is also important to note that, depending on how the fingers contacted the object, the friction was also impacted because of the complex geometry of the skin [14, 22, 36].

Besides all those elements, the mean of friction coefficient was calculated in the interval of grip force from 1 to 5 N for the two age groups. However, some elderly participants exerted more force during the trials (2 older subjects). To be more precise, the force range for the average friction coefficient should have been adapted on a case-by-case basis, according to the mean force applied during trials.

Therefore, we tried to evaluate the effect of friction during object lifting but there was an uncertainty on the values obtained for the coefficient of friction. Some subjects may have been excluded from the analysis because the relative difference in friction was lower than 10% while during trials, it may not have been the case. The opposite situation may also have occurred.

### Strain rate norm

As for the mean friction coefficient, the calculation of the mean strain rate norm was a large approximation. Indeed, per condition, we first computed the mean of the strain per participant. After, we computed the mean across participants. However, levels of skin strains varied greatly from subject to subject and then, this result was not very rigourous. For instance, F.Schiltz [14] noticed that levels of skin strains varied greatly from participant to participant. Again, a case per case study would allow to better understand the behaviour of each participant.

## Further analyses

Even if some interesting results have been obtained, it will be necessary and interesting to go deeper into the analyses. For example, it could be interesting to evaluate the rate of force increase during the loading phase and the duration of the loading phase, as Johansson and Westling [15] did. It will allow to confirm several of their observations for the two groups:

- the heavier the object, the faster the increase of the GF and LF during normal trials.
- the reliance of participants on stored information gained during the previous lift.

Another suggestion is to look at the safety margin of each participant, to confirm the fact that elderly participants had a greater one. More specifically, it would be appropriate to look at the difference between the actual GF/LF ratio and the slip ratio.

It would also be interesting to analyse the images in more details. In this work, mean strain rate norm was calculated but it will be more suitable to link the strain rate norm of a participant with its GF and LF curves.

Another idea would be to study the effect of double catch trials. Indeed, some trials of this type were carried out by the participants but were have not been studied in this work.

However, in order to have even more reliable results, it will be necessary to have more subjects, especially for the older group. Indeed, the variance across subjects within this group was large.

# Chapter 5

# Conclusion

This work aimed to identify the influence of age on finger pad mechanics during the lifting of objects. To achieve this goal, we designed an experiment with 28 participants divided into two age groups (18-35 and 55-75). The experiment consisted in a fast lifting movement followed by a static phase. During the experiment, weight and friction changes occurred without the participants noticing them. The forces data as well as the images collected during the experiment were compared between the two age groups.

First, results showed that friction coefficients of elderly participants were lower than those of the young participants. Moreover, the relative friction difference between the two friction conditions was higher for elderly than for young participants. It seemed to be due to skin changes associated with aging (i.e. dryer and less elastic skin).

Second, elderly participants seemed to correctly adapt to low friction. However, a lower tactile sensibility was reported in previous studies due to the loss of mechanoreceptors. Then, this better adapation could be due to the higher difference in friction coefficient. Indeed, the GF difference had to be higher between the two friction conditions than in the case of young participants. However, these results were to be taken with precaution given the few trials under these conditions.

Thirdly, elderly subjects seemed to adapt later to weight compared to young participants. The adaptation to weight was also slower than the adaptation to friction. Moreover, some older participants did not adapt during the weight catch trials while all young subjects did. Two different strategies seemed to be applied: young always minimized the enery spent while some elderly participants exerted higher forces than needed. Therefore, force applied during minimal weight trials was sufficient for maximal weight catch trials and there was no emergency to increase the GF level.

As a last element, the strain rate of young participants was higher than the one of elderly subjects. Another fact was that elderly participants experienced less full slip trials. It could be explained by the fact that elderly participants exerted more forces, leading to less partial slips and therefore, less strains. As a consequence, they received less tactile feedback. This excess of force could be a strategic response, due to the tactile sensibility impairment.

To conclude, the various results obtained in this work showed that there was a variability between elderly and young subjects. This could be due to sensory and motor changes, due to aging. Further research needs to be done to better understand and characterize thoses differences.

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# Appendix A

# Friction coefficients

## Young participants

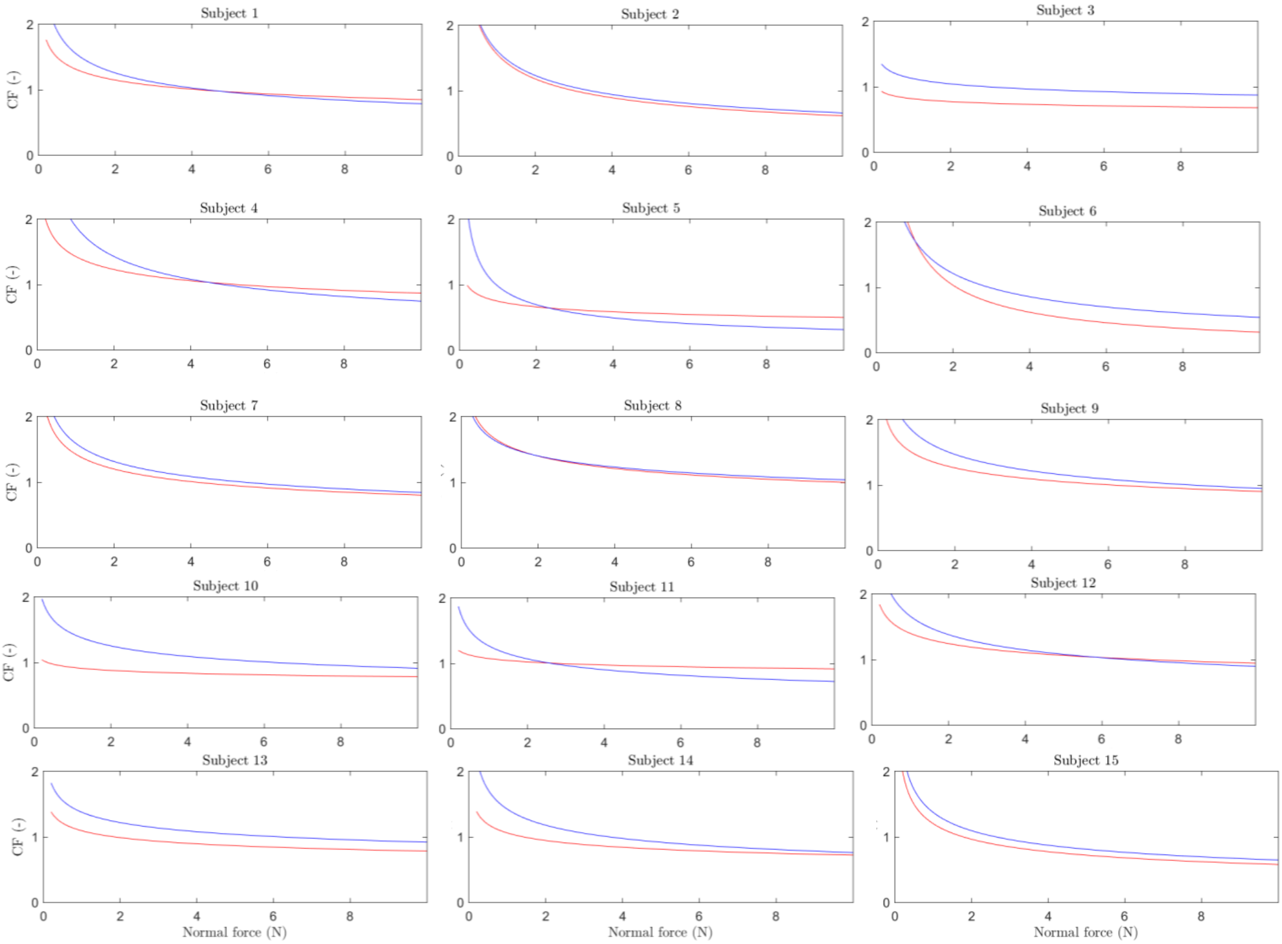

Figure A.0.1: **Friction coefficients of the index finger for young subjects.** Those curves are obtained using the method described in section 2.4. The red line corresponds to the low friction glass. The blue line refers to the high friction glass.

# Elderly participants

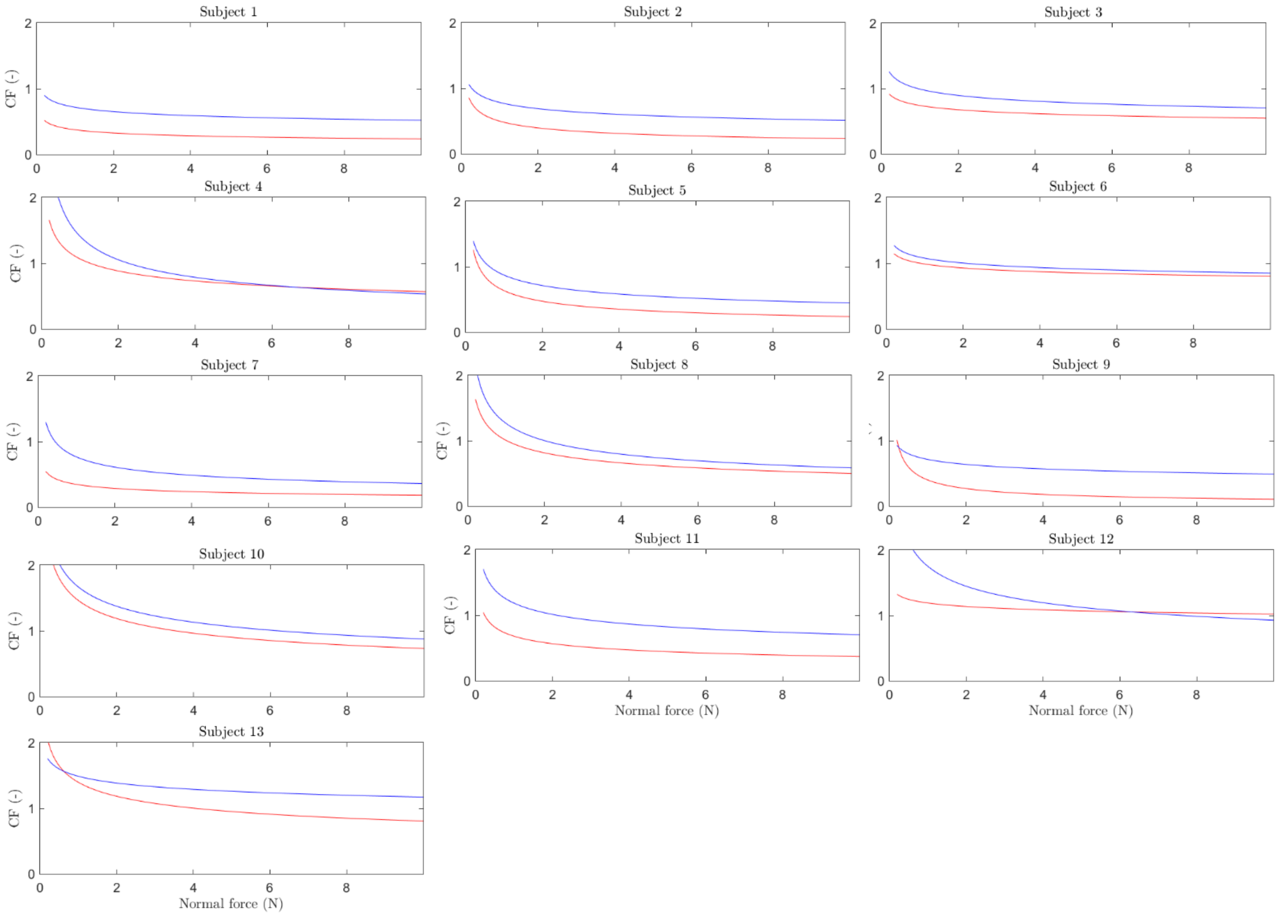

Figure A.0.2: **Friction coefficients of of the index finger for elderly subjects.** Those curves are obtained using the method described in section 2.4. The red line corresponds to the low friction glass. The blue line refers to the high friction glass.

# Appendix B

# Friction analysis - Case by case study

## Mean friction coefficients

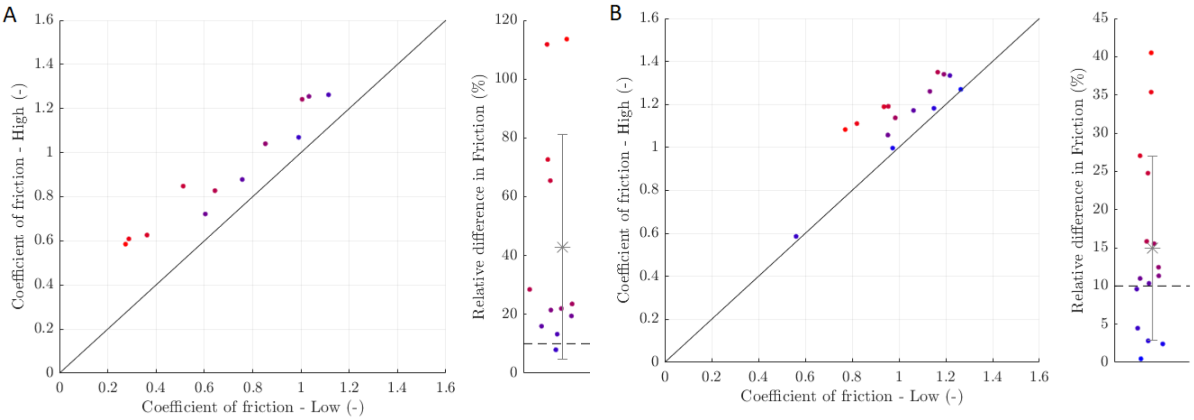

Figure B.0.1: **A:** Mean coefficient of friction of elderly participants. **B:** Mean coefficient of friction of young participants. In panels A and B, the participants with the lowest relative difference in friction are in blue while those with the highest are in red.

## Friction - Normal trials

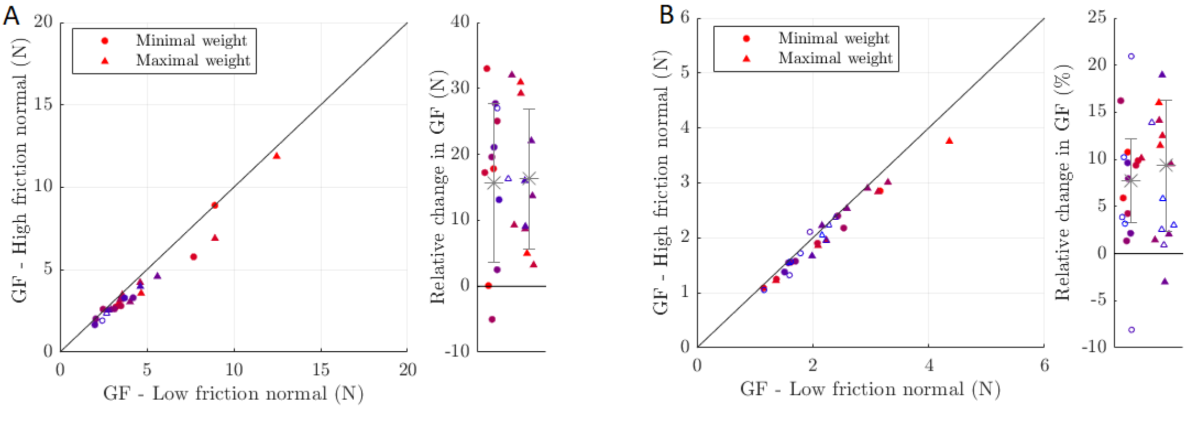

Figure B.0.2: **A:** Mean GF applied by elderly participants during static phase of normal trials. **B:** Mean GF applied by young participants during static phase of normal trials. In panels A and B, the participants with the lowest relative difference in friction are in blue while those with the highest are in red. Empty circles and triangles represent participants who had a relative difference in friction lower than 10%.

One could observe that, for both young and elderly participants, those who had the highest relative difference in friction were not necessarily those who had the highest relative difference in GF during the static phase of normal trials. Moreover, some participants excluded due to their relative difference in friction lower than 10% sometimes showed a relative difference in GF (empty circles and triangles).

## Friction catch trials

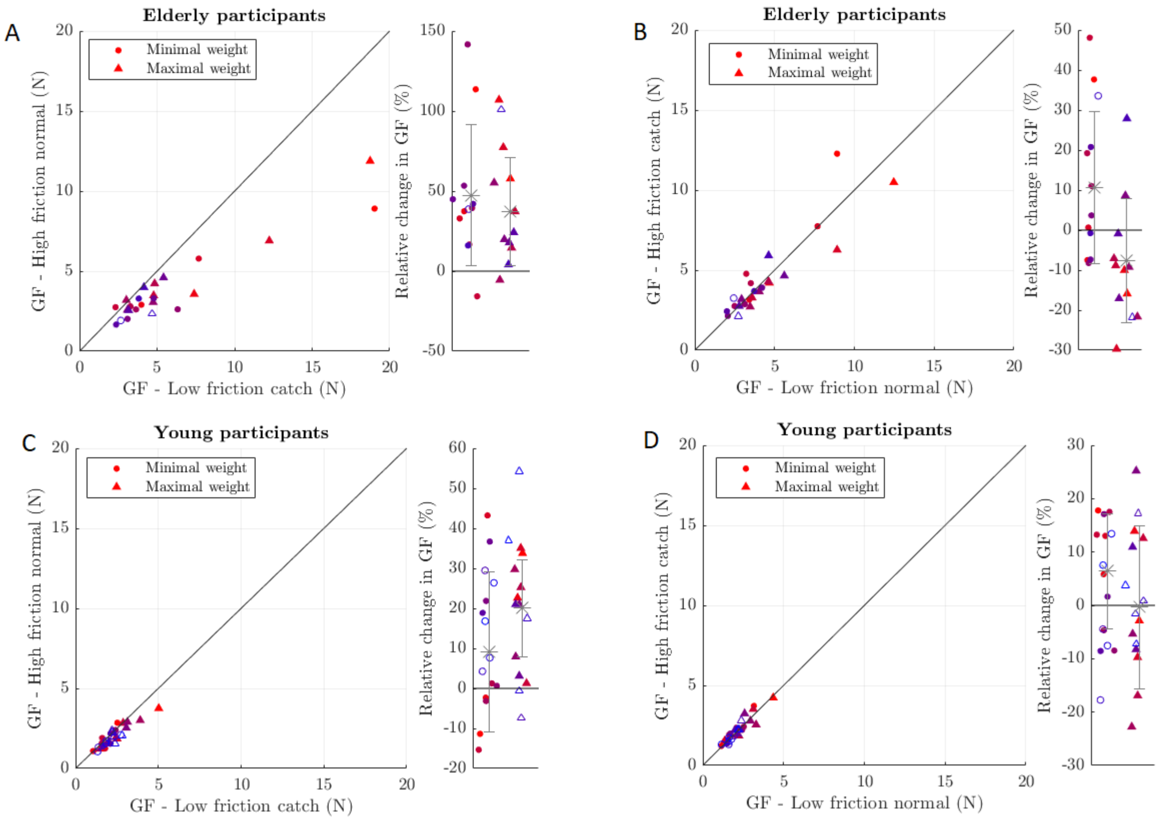

Figure B.0.3: **A:** Mean GF applied by elderly participants during static phase of low friction catch trial and high friction normal trials. **B:** Same as A but for high friction catch trials and low friction normal trials. **C:** Same as A but for young participants. **D:** Same as B but for young participants. In panels A, B, C and D, the participants with the lowest relative difference in friction are in blue while those with the highest are in red.

The same conclusion as for normal trials could be enounced: for both young and elderly participants, those who had the highest relative difference in friction were not necessarily those who had the highest relative difference in GF during the static phase of friction catch trials. Moreover, some participants excluded due to their relative difference in friction lower than 10% showed sometimes a relative difference in GF.

# Appendix C

# Adaptation to friction - GF curves of participants who had analyzable images

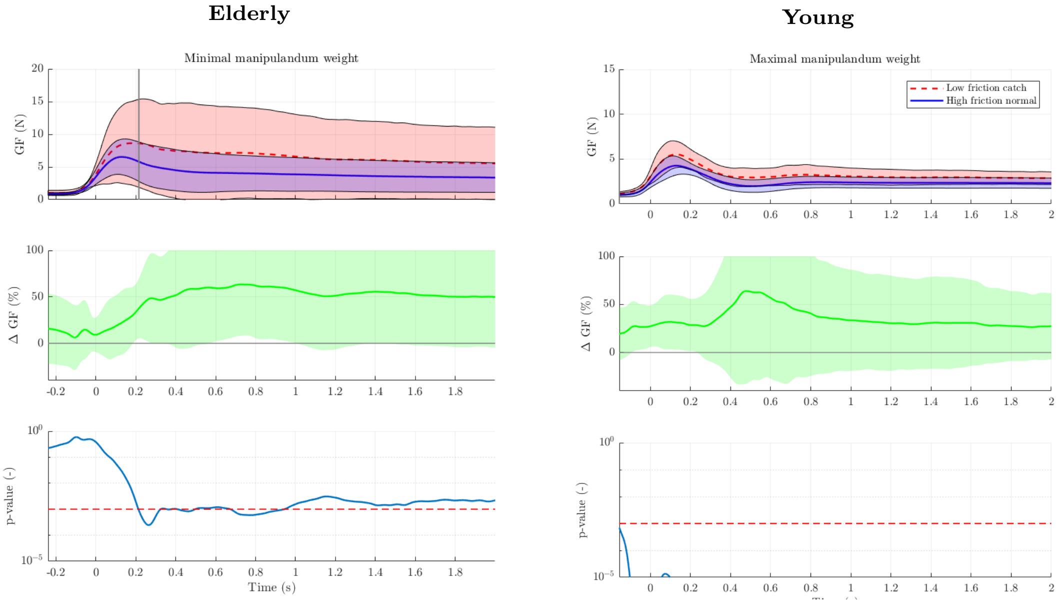

Figure C.0.1: **A:** Evolution of GF, ΔGF and p-value for low friction catch under minimal weight. Those curves were plotted with data from elderly participants who had analyzable images and who had a relative difference in friction higher than 10% (n=7). **B:** Same as A but under maximal weight, for young participants who had analyzable images and who had a relative difference in friction higher than 10% (n=8).

# Appendix D

# Adaptation to weight - Mean curves of participants who have not adapted

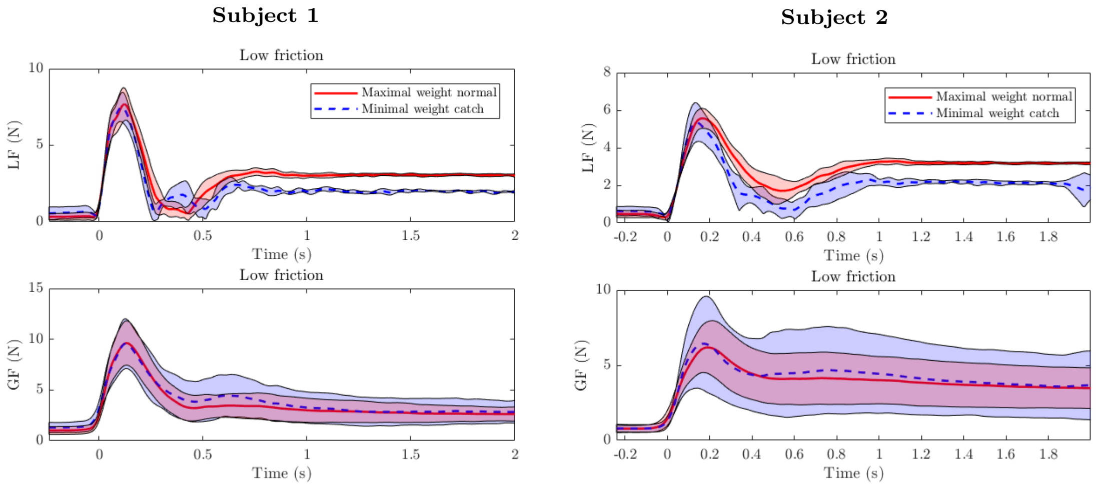

Figure D.0.1: Mean curves of participants who had not adapted to minimal weight under low friction.

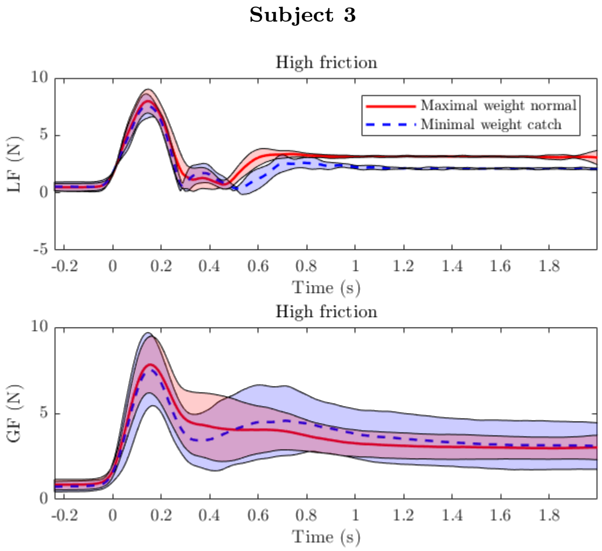

Figure D.0.2: Mean curves of participant who had not adapted to minimal weight under high friction.

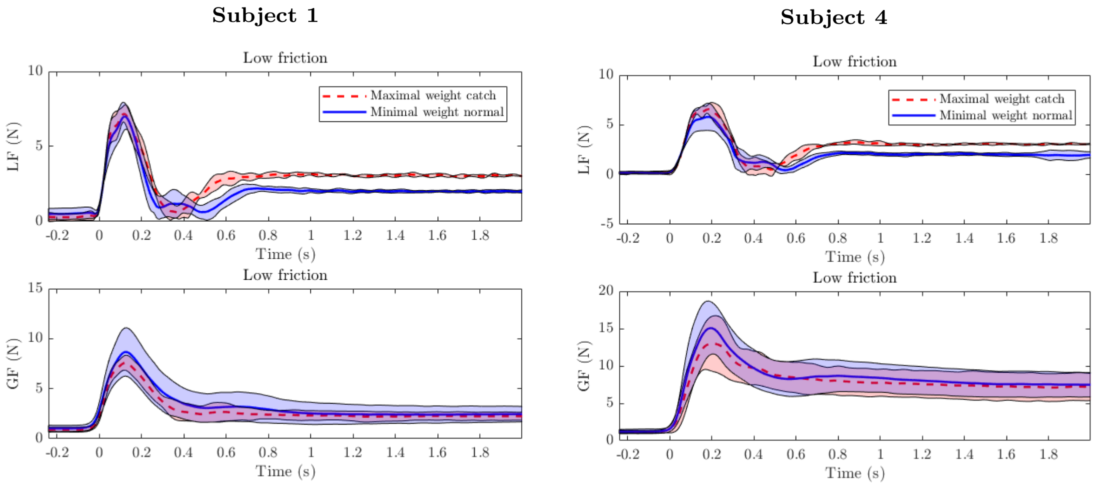

Figure D.0.3: Mean curves of participants who had not adapted to maximal weight under low friction.

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