

**École polytechnique de Louvain**

# **Experimental measurement of fingerpad deformation during active manipulation of objects with an off-centered mass**

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# Abstract

This thesis explores object manipulation with precision grip. In particular, we observe the changes due to the addition of an off-centered mass, causing a torque. Different levels of torques are studied to emphasise variations due to the torque level. We also aim to observe the adaptation of the subjects by doing catch trials for which we change the torque condition. During the catches, we can see the adaptation of the subjects, being first influenced by their previous experience, before catching up to the current condition to handle properly the new load. Finally, we try to identify the signals responsible for this adaptation. We mainly look at the torque on the fingers and the strains on the fingertip. This last is our main point of interest, we try to prove that the information from the deformations of the fingerpad is used by the central nervous system to identify the conditions of the object manipulation. These deformations could therefore initiate the adaptation of the subjects. This study aims to lead to a better understanding of the grip control that could be useful for patients' rehabilitation, disease diagnosis, and even treatment.

**Keywords:** object manipulation, precision grip, off-centered load, torque, fingerpad deformation, catch-trials, adaptation.

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Thank you,  
Thomas Desbrosses

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# Chapter 1

## Introduction

### 1.1 State of the art

Currently, our understanding of object manipulation is still limited. While carrying objects, our grip is adapted to some specific conditions. From simple ones like the object mass to trickier ones like skin humidity affecting the frictional properties of the contact interface, parameters are numerous. Previous studies showed the adaptation of the grip force after the addition of an off-centered mass [1]. They emphasised the slow adaptation of the grip through dozens of trials. This long-term adaptation is slowed down when an off-centered mass is attached to the manipulated object. Further studies were made in 0-gravity condition to isolate the effect of inertial torque [2]. Researchers conclude that the inertial torque is sufficient to slow down the adaptation of the grip, even though it seemed to be compensated quickly in previous results. It appears from another study that the mechanisms involved in the adaptation of the grip force to the tangential torque differ from the mechanisms allowing the adaptation of the grip force to tangential load [3]. These studies were interested in long-term adaptation, but not in short-term adaptation. Nevertheless, this situation can be a daily life issue as we constantly manipulate different objects for which we can not know the grip condition in advance. There should be a mechanism to allow the adaptation of the grip almost instantaneously to maintain a stable manipulation of various objects. This adaptation is studied through catch-trials for which we change the off-centered load unbeknownst to the subjects.

The next step of this study is to determine a signal responsible for the adaptation of the grip. Previous studies revealed distinct response components with distinct reaction times that could correspond to different sensorimotor circuits [4]. Despite the importance of both tactile and muscle afferent feedback seems to be accepted, these studies did not identify the causal role of muscle or tactile afferents in the

generation of the motor response. Other results showed a link between the fingerpad deformations and the contact conditions. In particular, the stick area of the finger during slipping varies with the normal force and the slipping speed [5]. Further studies emphasised the differences in strains given the load direction [6]. It concludes that strain schemes are strongly different given the load direction. These differences could give us information about the contact properties. The idea is that the tactile mechanoreceptors embedded in our fingers send signals to the brain through action potentials [7] [8]. These potentials give an idea of the mechanical properties of the contact between the finger and the manipulated object. To confirm this idea, an experiment was made to determine the detection threshold of slipping [9]. It was shown that subjects can detect slipping before full-slipping occurs. Therefore, humans can detect a future slipping before it happens. This confirms again that skin deformation could be responsible for detecting an upcoming slipping, and therefore initiate the grip adaptation to avoid this slip. Other recent studies tried to isolate the effect of tactile information to observe its own effect [10]. They manage this by controlling the direction of skin deformation relative to the force applied to the finger. They observed that a deformation in the same direction of the force field slows down the adaptation to the force field but increases the modulation between grip force and load force. On contrary, deformations in the opposite direction of the force field improve the adaptation with no effect on the applied grip force. These results show again the clear impact of sensitive information from skin deformations in grip control and adaptation. Therefore, the human tactile sensory system seems to be a key aspect in our understanding of grip control. And study the behavior of the fingertip during active manipulations becomes crucial to fully understand the adaptation of the grip given the daily-life specific conditions.

## 1.2 Goals and purposes

The purpose of this study is to observe our behavior while manipulating objects with an off-centered mass. Two aspects are merged: the study of the fingertip and grip control with a tangential torque. Both dynamics and kinematics are involved and observed during the active manipulation, as well as the fingerpad deformations against the object. The effect of a catch is also highlighted to show the grip adaptation to an unexpected torque condition. During these catches, anticipation and adaptation are limited, while the pure reaction to a different stimulus is emphasized. The skin strains are studied as a possible source of information to distinguish the different torque conditions.

This study aims to give answers to the grip adaptation mechanisms. Indeed we currently do not have deep knowledge in this field as the involved signals are not

precisely known. The results may be useful for medical rehabilitation purposes and also as fundamental research to better understand the global behavior of the human body. Medical applications resulting from this field are broad as it implies many crucial functions. From rehabilitation after a stroke to developing treatment or diagnostic tools for diseases like Parkinson that affect our motor control. Or even designing a prosthesis that can interact with the nervous system as a normal arm would do.

# Chapter 2

## Methods

### 2.1 Setup

#### 2.1.1 Initial setup

The experiments are realised using a setup developed during the past few years called ActiveTouch, a picture of the initial setup is shown in FIGURE 2.1. The initial purpose of this manipulandum is to be able to observe the fingerpad deformations while we manipulate the object itself. It allows vertical movements using a bi-digital grip, usually with the thumb and the index.

Forces and torques are measured in real-time using two force sensors. The kinematics of the movement is also observed thanks to an accelerometer and a laser for the vertical position. The main parts of ActiveTouch are represented in FIGURE 2.2 and their respective purpose are the following.

- **Accelerometer:** The three-dimensional accelerometer is placed at the top of ActiveTouch. It is used to get information on the kinematic of the movements that are performed. It is also used to measure the tilt angle in a static phase.
- **Force sensors:** The force sensors are placed on the upper part of ActiveTouch just below the accelerometer. Two plates are screwed to them. These plates carry the glasses that allow both force measurements and visual observation.
- **Glasses:** The glasses are the contact area between the fingers and ActiveTouch. There are wisely placed between the camera and the force sensors to allow both measurements.
- **Camera and mirror:** The camera is placed at the lowest of ActiveTouch. It can capture images of the finger thanks to a mirror placed at a 45 degrees angle. A light source is coming from one side of the mirror while the other side is recorded.



Figure 2.1: Picture of the initial setup

- **Pulley:** The pulley is used to limit the vertical load of the device thanks to a counterweight.

### 2.1.2 Design

The design step aims to adapt the setup to apply a torque. The first change consists of adding a rod that allows fixing a mass to it at a certain distance from the center of mass. This rod has an "L" shape, it is attached to the top of ActiveTouch and go down to the glasses level, as it is shown in FIGURE 2.9 and FIGURE 2.10.

The main challenge is to get a setup that does not compensate for the torque when tilt appears. In particular, the pulley was a question mark. At first, the pulley was attached to the manipulendum using string, as it is illustrated in FIGURE 2.3. It was sufficient for its initial purpose which is handling a part of the vertical load, but it had a clear non-negligible impact on the torque. As soon as the tilt angle of the manipulendum increases, the torque will decrease. First, because ActiveTouch is getting closer to its equilibrium but we can not avoid it to happen. Second

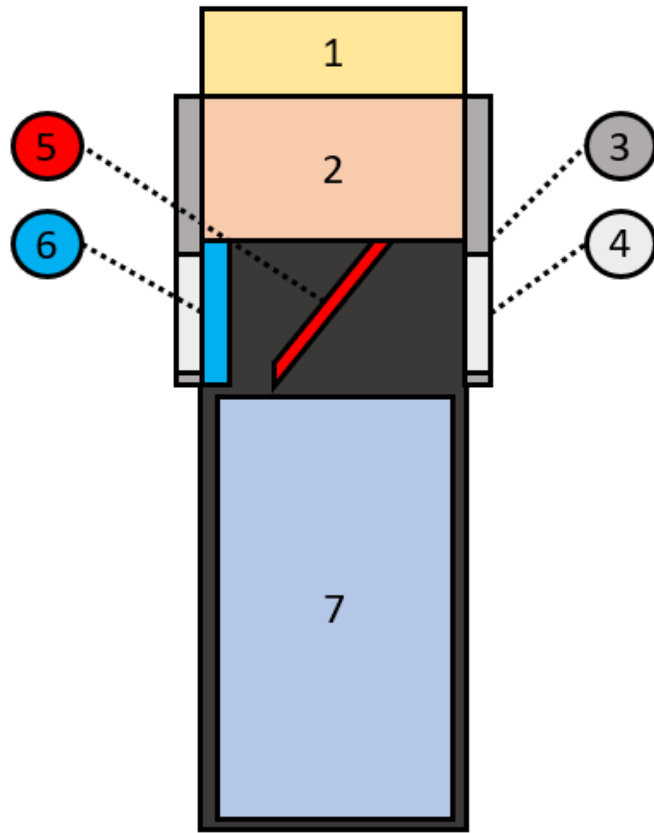


Figure 2.2: Scheme of the initial setup : (1)Accelerometer - (2)Force sensors - (3)Plates (4)Glasses - (5)Mirror - (6)Light - (7)Camera.

because the pulley, in particular in the current configuration, will also compensate for a large part of the torque as soon as tilt occurs.

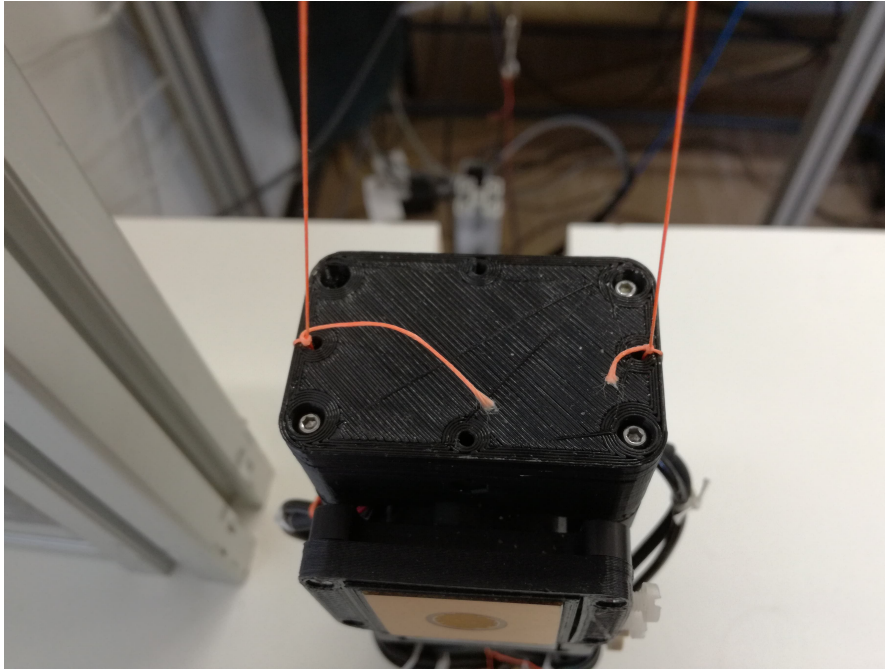


Figure 2.3: Old attachment system to the pulley

The main idea is then to attach the pulley on a single axis around which ActiveTouch could rotate freely. By doing that, adding a torque would cause the manipulandum to rotate around this axis and therefore almost nullify the torque loss in the pulley system. An optimal position for this axis was determined theoretically and verified experimentally. Two possibilities were mainly studied. The first one is the axis that is aligned with the fingers and so the glasses, a scheme represents the straight and tilted situation in FIGURE 2.4. The second one is the axis that goes through the center of mass of the manipulandum, a scheme represents the straight and tilted situation in FIGURE 2.5.

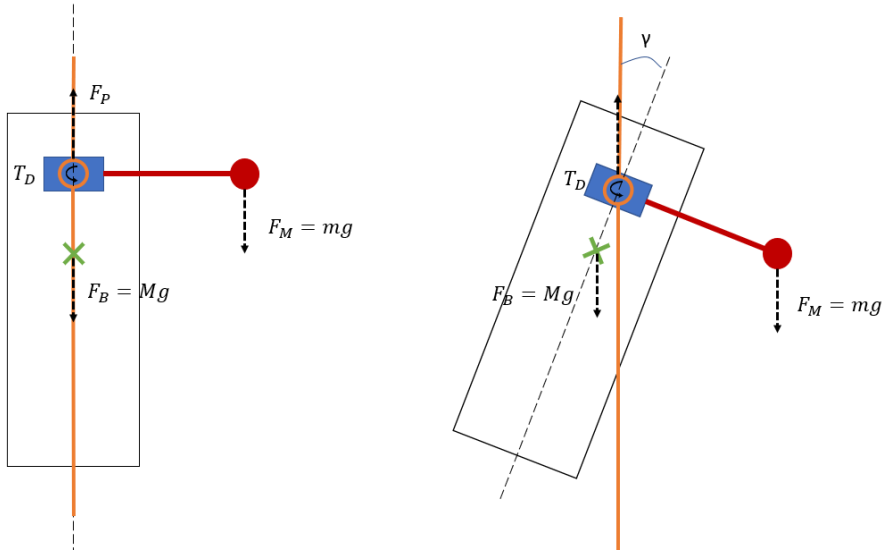


Figure 2.4: Scheme of ActiveTouch with an attachment axis at glasses level

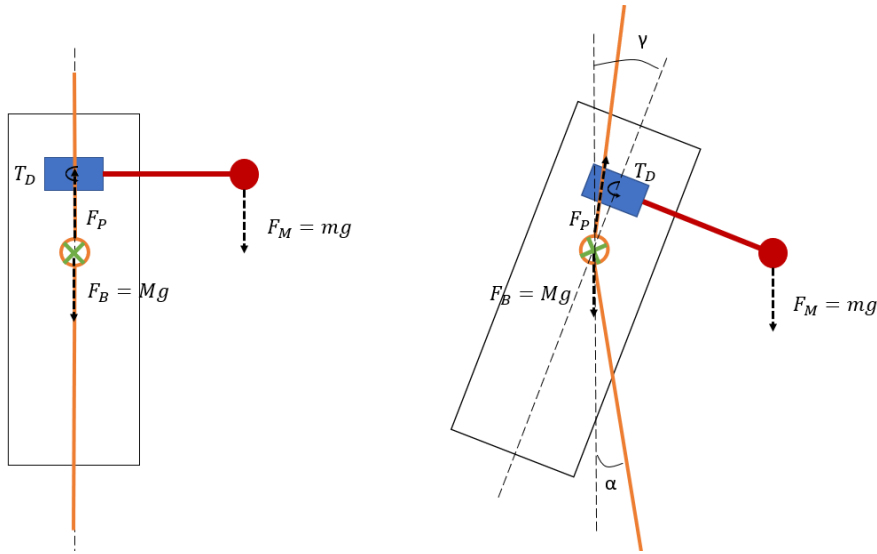


Figure 2.5: Scheme of ActiveTouch with an attachment axis at center of mass level

These schemes allow a first theoretical evaluation of the best solution. We want the solution to have a limited torque variation when the tilt angle increases. A graph depicted in FIGURE 2.6 shows the normalized torque applied to the fingers given the tilt angle. We can see that the torque decreases when the tilt angle goes to the negative, which means toward the equilibrium. There is a great difference between the two solutions, and the second one seems largely better.

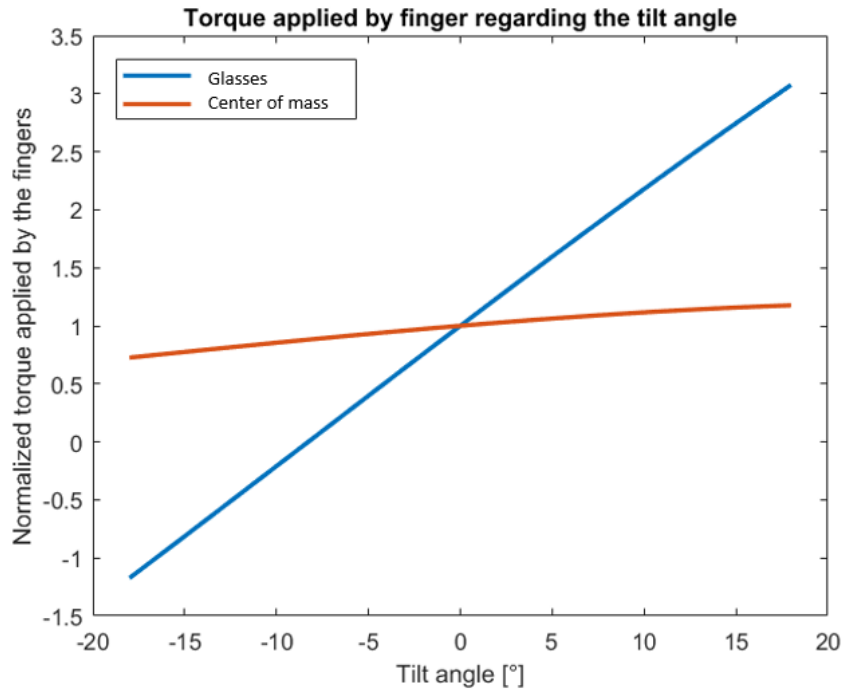


Figure 2.6: Normalized torque applied on the fingers given the tilt angle of the manipulandum for the two possible axis position

To study these solutions experimentally, an intermediate setup was designed. This setup aims to allow variation of the axis position. We could try different possibilities including the two most interesting ones: the glasses level and center-of-mass level. This testing design was first realised on Solidworks and the result is depicted in FIGURE 2.7. The extra part, coming from the top of ActiveTouch, allows the fixation of the two attachment points at different heights.

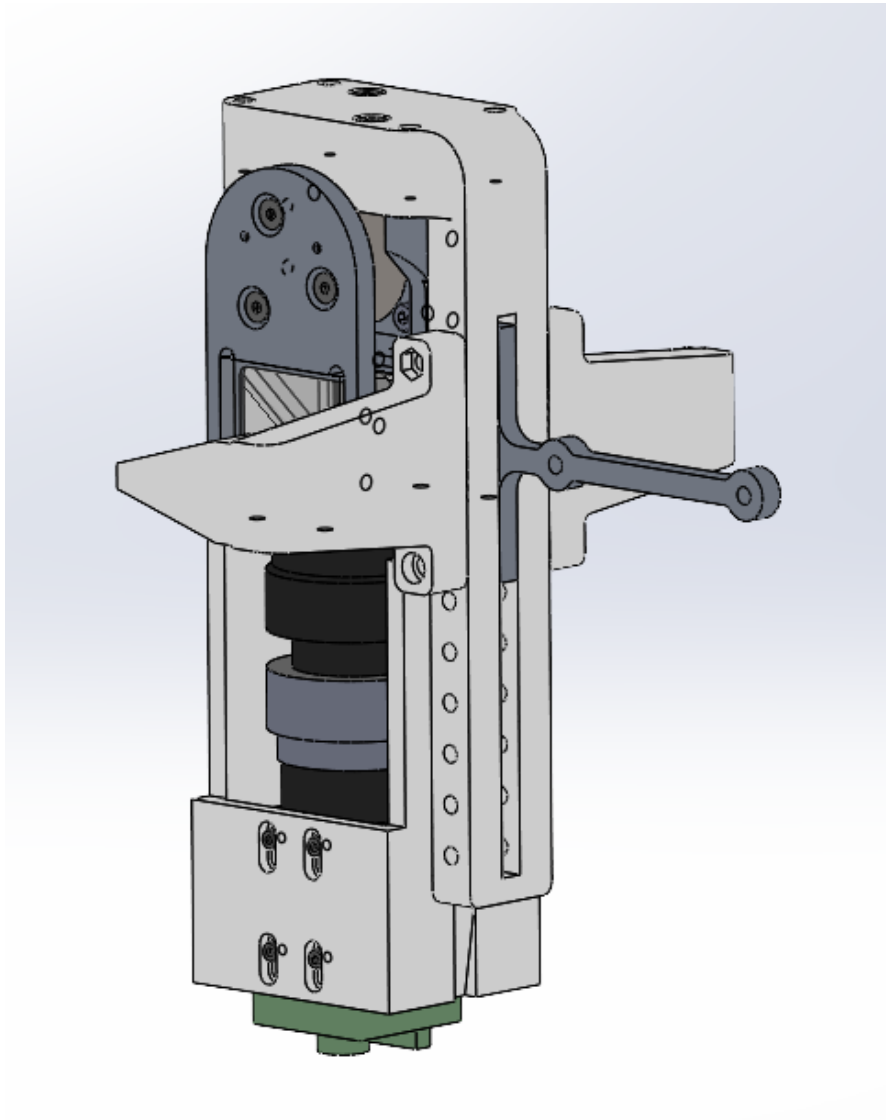


Figure 2.7: Capture on Solidworks of the testing design

This setup was finally used to perform experiments to compare the two main solutions. Results are shown in FIGURE 2.8. We observe the evolution of the torque during a simple manipulation, and we focus on the static phase at the end of the experiment. At the end of the static phase, around 50 seconds, the tilt angle in both cases was worth around 4 degrees. We can again see that the first solution shows a way greater torque loss when the tilt increases. Moreover, the losses that we observe experimentally are consistent with the prediction of the theoretical model.

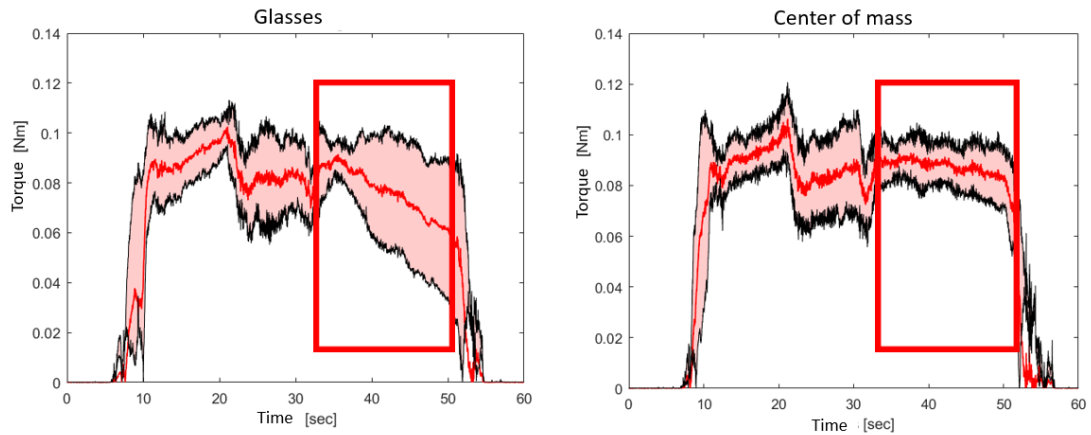


Figure 2.8: Total torque measured during simple movement, averaged over 10 trials. Left graph has its axis at glasses level, right has its axis at CoM level

The final and best design is then the second one, with an axis around the center of mass.

### 2.1.3 Final setup

The final version of ActiveTouch is first designed on SolidWorks and can be seen in FIGURE 2.9.

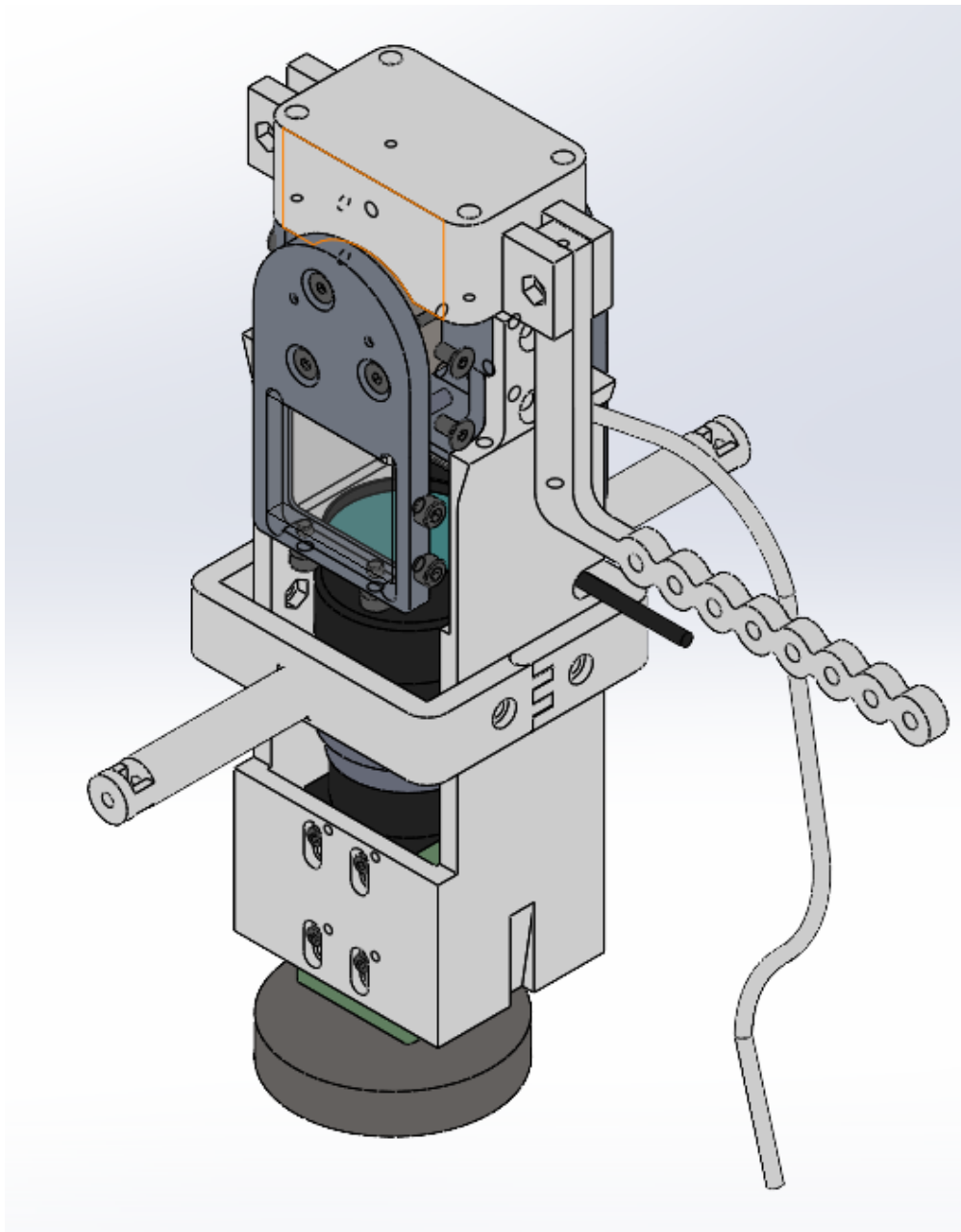


Figure 2.9: Caption of the final design from Solidworks

A picture of the real model in FIGURE 2.10 shows the manipulendum attached to the pulley in its rest position.

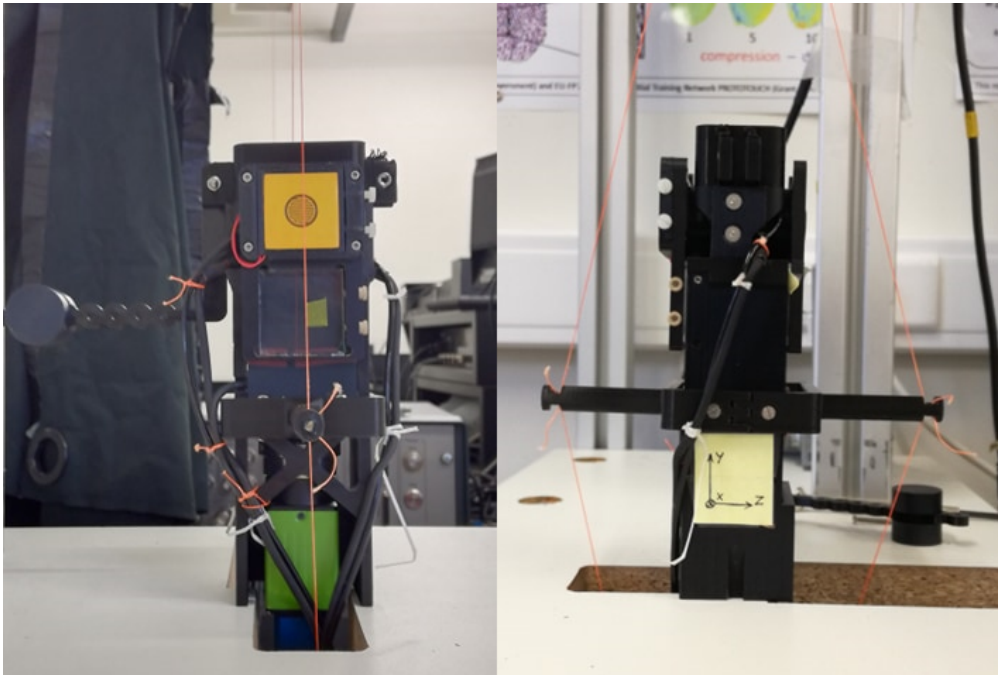


Figure 2.10: Picture of the final version of ActiveTouch, set up in the laboratory

To end the full description of the setup, the pulley is attached to a counterweight to limit the vertical load. It has been shown in past experiments that limiting the vertical load gives better results as the subjects are more comfortable while performing the experiment. An additional mass is hanged below the manipulandum. This mass is added to even the vertical load between the different conditions. Doing so, changing the torque condition only affects the torque and not the load so we can isolate the impact of the torque. A picture of this weight and the vertical load measured for each condition is shown in FIGURE 2.11

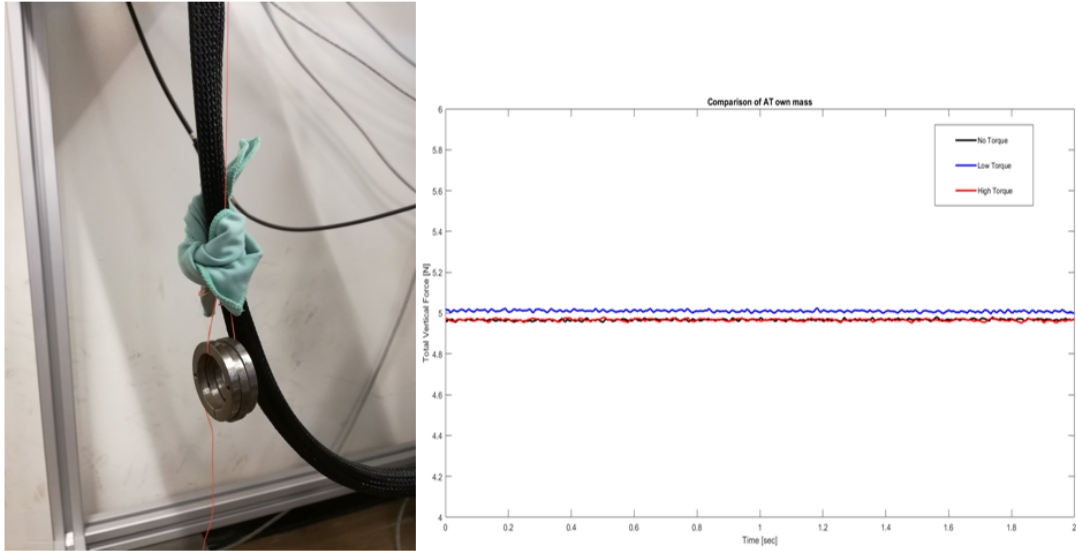


Figure 2.11: On the left, picture of the additional weight. On the right, measure of the vertical load for each torque condition

## 2.2 Experiment

We asked 12 subjects to perform the experiment. All subjects are right-handed and have no known trouble or disease that would impact the results. Some subjects are familiar with the experiment purpose and the device, some are less and others are completely naive about both setup and purpose. The experiment for one subject takes two to three hours, depending on the breaks he needs.

Each subject will perform 150 movements, divided into blocks of 5 measures which leads to 30 blocks. The first three blocks are considered as learning blocks to allow subjects to get familiar with the device. The associated results will not be taken into account in the final results. Between blocks, the torque condition will change among three possible values: No-Torque (T0), Low-Torque (T1), and High-Torque (T2). This torque load is adjusted by changing the off-centered mass value. The torque sequence is unique for all subjects and wisely designed. We start with the learning blocks that are T0 blocks. Afterward, we placed the same number of blocks for each torque condition. We also even the transition number as we aim to study the catch trials in particular. We end up with a sequence containing 3 learning blocks, 9 blocks of each condition, and 4 transitions of each possibility. We added a control transition for each condition, for which we do not change the torque level between two blocs. The final sequence is given in TABLE 2.1.

The movement to perform is simplified to limit variance across trials. First,

Block	1	2	3	4	5	6	7	8	9	10
Condition	T0	T0	T0	T0	T1	T2	T0	T2	T1	T0
Block	11	12	13	14	15	16	17	18	19	20
Condition	T2	T0	T2	T1	T0	T1	T1	T0	T1	T2
Block	21	22	23	24	25	26	27	28	29	30
Condition	T1	T2	T2	T0	T2	T1	T0	T1	T2	T0

Table 2.1: Torque condition sequence

subjects must take ActiveTouch with their right hand using only their index and thumb. They have 10 seconds to adjust the position of their fingers and their grip force. The finger position is displayed on a computer in front of the subjects thanks to the camera. It is asked to the subject to place their index in the center of the glass, slightly downed to anticipate possible rolling or slipping of the finger during the lift phase. The grip force is also displayed on a computer and we ask the subjects to stay as constant as possible at 1N of grip force before lifting. Doing so we want again to limit the variance across trials from non-desirable effects. After 10 seconds, subjects have to lift the manipulandum around 20 centimeters above its platform. The targeted height is visually indicated to the subjects with a color band. Two sound signals tell the subjects when he should start and end the lifting, to command the movement kinematic. Once lifted, subjects hold the device for two seconds and a final sound signal tells them to put it down on the table. The descending movement is not as controlled as the rising one as we will not study it. Some instructions were given to the subjects before starting the experiment. First, they had to wash their hands to remove any impurities for the camera, after that other instructions were given to let them some time to get fully dry. The highest priority for the subjects is to keep a two fingertip contact with the manipulandum. The two main risks are to add the second phalanx of the index and to touch the device with the hand. Both would lead to incorrect results that we could not interpret. The second priority is to limit the tilt of ActiveTouch during the experiment. We have a good idea of the tilt during the static phase thanks to the accelerometer, but we want to limit it since it lowers the torque that we aim to apply. Moreover, tilt has to be limited to a few degrees or the cables from the camera will get in contact with the table, creating a counter torque that we never want to appear. The third priority is to lower the grip force as much as possible. It is mostly relevant for the T0 condition where a low force is required, an overpressure from the fingers is not desired since it is not realistic and it makes the visual analysis more complicated. Finally, the subjects should be comfortable during the experiment, sitting or standing, and should not try to interpret the experiment's purpose.

# Chapter 3

## Results

This section is divided into three main sections: global results, single subject, and generalisation. The first section focuses on the global mean between all twelve subjects and gives an idea of the general differences between the three conditions. We did not look at the mean of the strains from the camera data. The second section adds the camera data and focuses on one particular subject to try to make links between camera and sensors data. In this section, we mainly focus on the two extreme conditions T0 and T2. We also dissociate the catch trials and regular ones. We consider the first measurement of each block as a catch while the following four are regular. In the third section, we compare what we observe in the previous section with the others subjects. We try to deduce general rules or to identify different strategies and classify them. We also briefly discuss the difference with the T1 condition that was not analysed in previous sections.

### 3.1 Global results

In this section, we focus on observing the differences between the three torque conditions on average. The graphs show the different data acquired and are synchronized on the maximum load force. In general, we use the same color legend: black line for T0, blue line for T1, and red line for T2. We observe the general means of all measurements of all subjects and show it with a 95% confidence interval around it.

#### Load force

The first quick observation that can be done to check our setup and assumptions is the total load force. Actually, it should be the same no matter the torque condition, as we compensate the loss of off-centered mass by a centered mass in lower torque

conditions. As we can observe in FIGURE 3.1 the total load force is even for the three conditions which will allow us to observe the pure impact of torque without tangential load change.

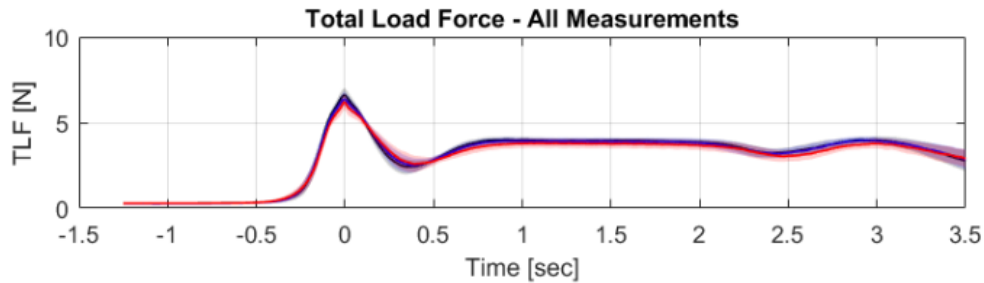


Figure 3.1: Evolution of the average total load force given the torque condition : T0 in black, T1 in blue, and T2 in red

## Position

The analysis starts with the observation of the position measurement to get an idea of the movement kinematic. The position graph can be seen in FIGURE 3.2. First, we can notice that the movement starts around 0 sec on the time axis. The lifting part of the movement is well calibrated as we wanted as the variance is low. The end of the movement shows more variance as we do not try to control it with sound signals. The torque condition seems to impact slightly the kinematic of the movement, a higher torque seems to slow down the lifting movement.

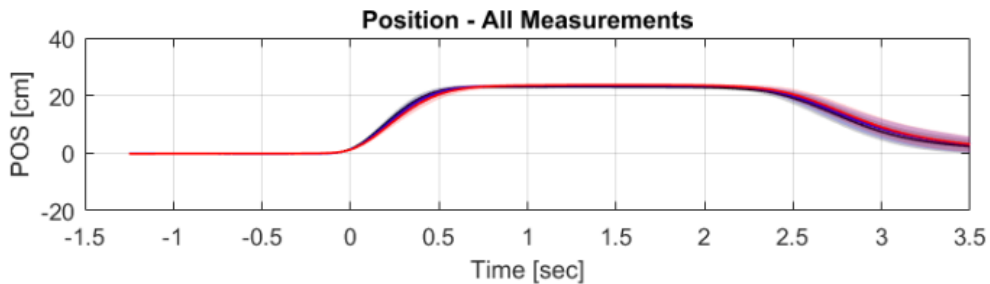


Figure 3.2: Evolution of the average vertical position given the torque condition : T0 in black, T1 in blue, and T2 in red

## Tilt angle

To complete the kinematic comparison, we use the accelerometer data to compute the tilt angle of the manipulendum around the fingers' axis. The tilt angle is a

crucial measurement as it largely impacts the torque and the off-centered mass could induce a tilt. As we can see in FIGURE 3.3, the torque level impacts the tilt angle. A higher torque leads to a higher tilt on average, this is not surprising as the torque tends to make ActiveTouch tilt forward. When the tilt increases, the torque decreases as we go toward the equilibrium position. We can deduce that the higher tilt is caused by certain subjects that are not able to handle the full torque load and then let the tilt increase until they can hold it. It is also interesting to notice that the tilt angle in the no-torque condition is slightly negative. It means that at least some of the trials show this behavior when subjects create an unnecessary angle toward the hand. We can also notice large variations of the tilt during lifting and deposit phases but this is due to the acceleration during movements. As we deduce the tilt angle using gravitational acceleration variation that we measure with the accelerometer, the acceleration required to move the object impacts this result and makes the tilt estimation imprecise.

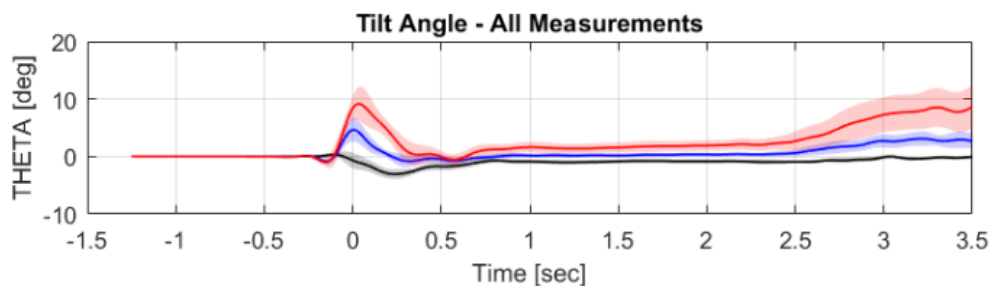


Figure 3.3: Evolution of the average tilt angle given the torque condition : T0 in black, T1 in blue, and T2 in red

## Grip force

The remaining data, captured with the force sensors, are torques and forces in 3 directions. We focus on the total main torque around fingers' axis and the grip force, normal to the interface between the fingers and the manipulandum. We first look at the grip force. The grip force is the main control that we have during active bi-digital manipulation. Even to counteract the torque added by an off-centered mass, increasing the grip force seems to be the way to deal with this torque. By increasing the grip force, friction forces will increase between the fingers and the manipulated object. This friction will mainly allow to handle the torque and maintain the device straight. The grip force measured during the experiment can be seen in FIGURE 3.4. As we expected, the grip force has to be adapted to the torque condition. We see a clear difference between the three conditions in terms of grip force level. The overshoot at the start of the movement seems to decrease

with higher torque while the decreasing slope during the static phase increases with higher torque.

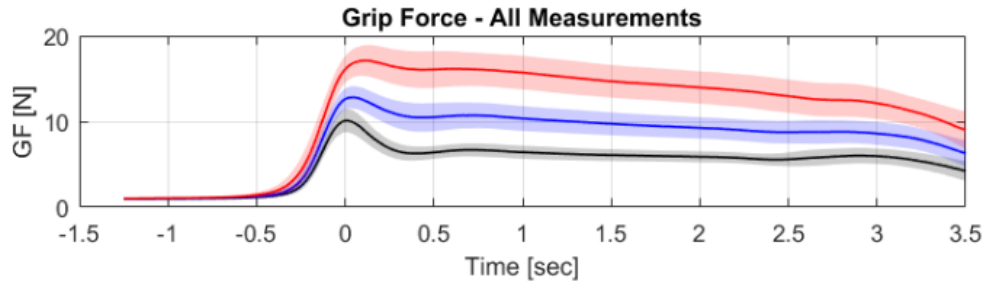


Figure 3.4: Evolution of the average grip force given the torque condition : T0 in black, T1 in blue, and T2 in red

## Torque

The torque shows similar behavior as the grip force. The three levels are clearly different, which was expected because the conditions do not have the same torque load. The theoretical loads of the different conditions are respectively:  $0.00Nm - 0.0378Nm - 0.0648Nm$  for T0, T1, and T2. In the high torque condition, the torque level seems to decrease below the theoretical level, probably linked with the tilt increase that we saw before. We also see a positive torque in the no-torque condition, with an overshoot that is not present in other conditions. This positive torque can again be related to the tilt measures where we observed a slightly negative tilt for this condition. This applied torque would explain the change in tilt angle. The overshoot in torque is probably mainly due to the catch trials for which subjects are used to apply torque from previous trials. To verify this idea, we should compare catch trials and regular trials, this will be done in the next section.

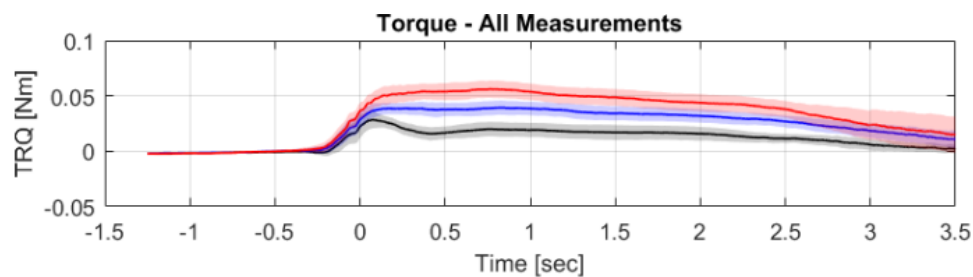


Figure 3.5: Evolution of the average torque given the torque condition : T0 in black, T1 in blue, and T2 in red

## Adaptation

Having now an idea of how the forces behave during the experiment, we want to see the differences between the trials. In particular, we want to observe the catch trials and the impact of the previous condition on the behavior. To have a first quick look at it, we observe the evolution of maximum grip force for each trial. The result can be seen in FIGURE 3.6. We can again observe a clear difference between the conditions as we could already observe. What we want to observe here is the first measure of each block. In general, we see an adaptation of the maximum grip force in one block. The catch trials, the first trial of each block, is hardly impacted by the previous condition. The most visible impact happens for transitions between the two extreme conditions T0 and T2. When the subjects just made 5 trials with a T0 condition, he adapted his grip force and his general behavior to this particular condition. When the condition suddenly changes, his memory will make him perform the same movement but the condition has changed. Coming from a T0 block, the first trial of a T2 block shows a much lower maximum grip force on average. The same behavior happens when the torque is lowered. After getting adapted to a high torque during 5 trials, the first trial of a no-torque condition shows a higher maximum grip force.

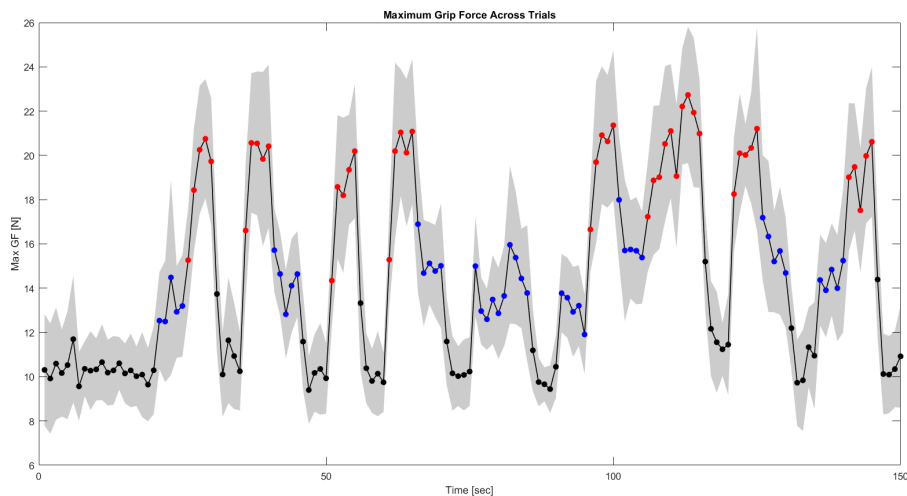


Figure 3.6: Evolution of the maximum grip force across all trials. Mean results between all subjects, data are colored following the torque condition : T0 in black, T1 in blue, and T2 in red

We can also emphasise the adaptation over the five trials of each block. In FIGURE 3.7 we can observe the evolution of maximum grip force among the 9

blocks of each condition. Each graph shows the evolution of one particular trial, the first one, then the third one, and finally the last one. What we can see is the huge impact of the previous condition for the catch trials as the grip force varies a lot depending on the block. The third trials show less variation meaning that the subjects are already adapted to the new condition. The last trials show even less variation in average, the subjects are even more adapted and the variations become almost irrelevant. This information is a good feedback for the protocol design. We observe a good adaptation after only 5 trials which allows us to compare catch trials and adapted regular trials.

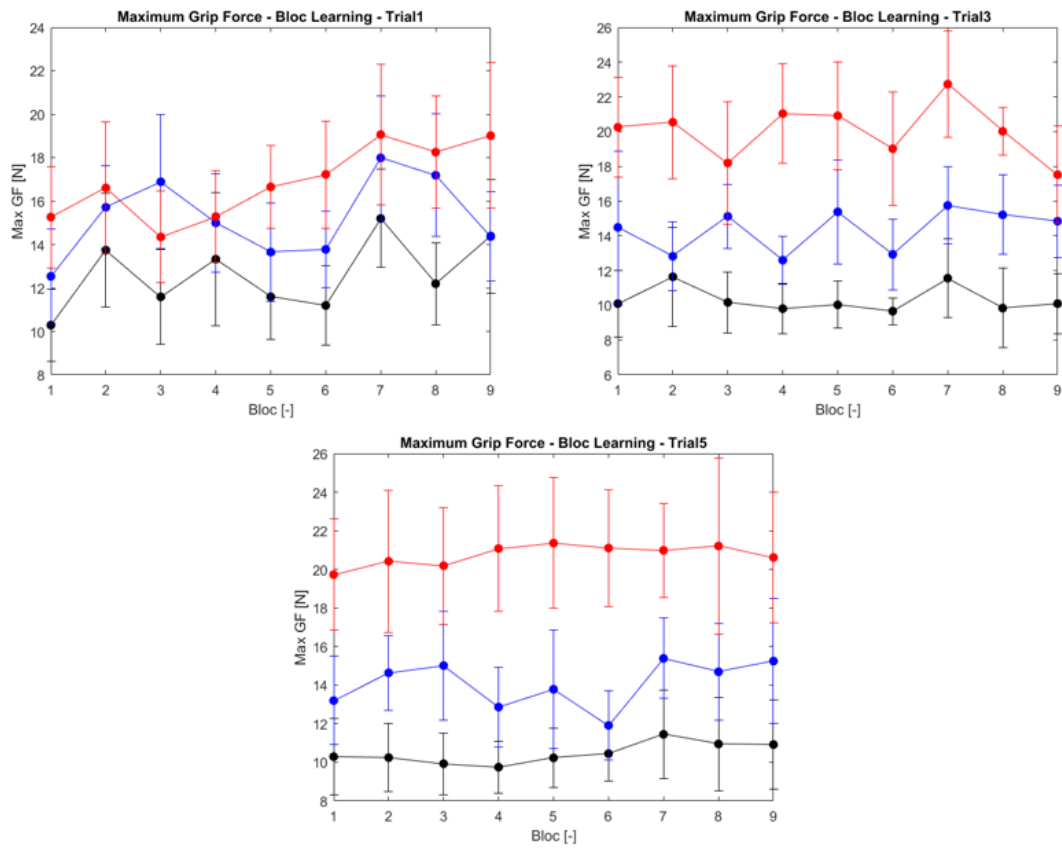


Figure 3.7: Evolution of the maximum grip force across the blocks. Each graph shows the evolution of one of the five trials, here the first, the third and the fifth. Mean results between all subjects, data are colored following the torque condition : T0 in black, T1 in blue, and T2 in red

## 3.2 Single subject full analysis

In this section, we focus on the analysis of one particular subject, the seventh one. The behavior of this subject will be analysed in detail before being compared to the other subjects in the next section. In particular, we focus here on the two extreme conditions T0 and T2. We analyse the force sensors data in parallel with the camera data and so we try to link the forces and torques with the fingerpad deformations. We also go more deeply in the analysis of the particularities of catch trials. The choice of the studied subject was arbitrary and mostly motivated by the quality of the images. Moreover, this subject showed good behavior during the experiment and his forces measurements are satisfying. Finally, we start now to try finding the signal responsible for the adaptation of the grip. Beyond the descriptive analysis of the behavior given the condition, the objective is to determine which signal is responsible for the grip changes. The two studied hypotheses here are the torque and the fingerpad deformations. Indeed, the torque itself felt by the subjects could give him the information needed to adapt his behavior. The second theory is that the deformation of the fingerpad would trigger some action potential depending on the deformation. These signals could be analysed by the brain to deduce the current conditions of the grip and then allow us to adapt it. Both can also play a role in parallel in the adaptation.

### Position

The average position and speed of the vertical movement are displayed in FIGURE 3.8. We see the impact of the torque in the kinematic of the movement. The presence of an off-centered mass slows down the lifting movement. The initial acceleration is lower as well as the maximum speed. The deceleration is also slower in this case because of the object inertia but it also compensates for the slow lift to get to the desired height.

The first observation is that this subject adapts his movement to the torque condition. The adaptation is really fast as it seems to begin even before the movement itself, the initial slope of increasing speed being lower in the high torque condition. The adaptation of kinematic can be linked to the dynamic as the speed impact the inertial torque. Actually, torque is composed of a static part, depending mostly on the load, and an inertial part, which depends on the load and the acceleration. So adapting the kinematic can be a strategy to make the grip adaptation easier, as limiting the speed will limit the required grip force.

The impact of the catch is here not clear as they follow the same behavior as regular trials. The only visible effect is small oscillations of the speed at its peak, but it can be due to the lack of data for this condition. Indeed, as we focus on one subject and one transition, our sample for this particular case is made of only four trials.

A signal responsible for the adaptation of the subjects should then appear before the movement begins.

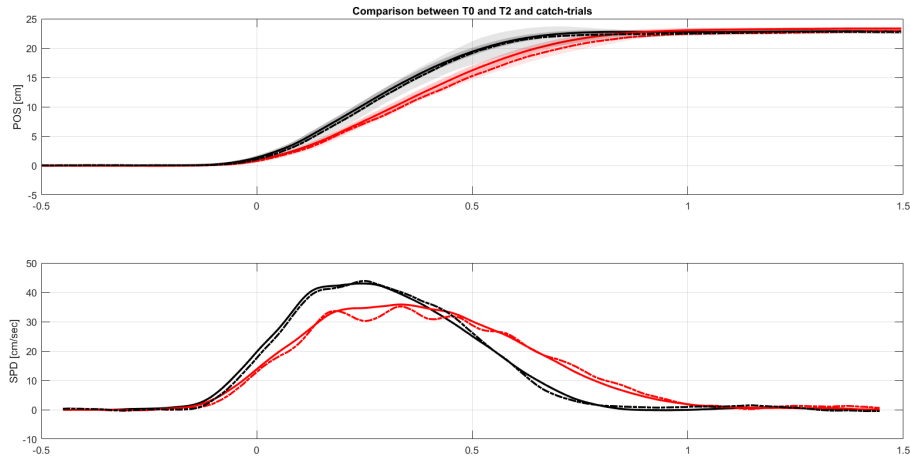


Figure 3.8: Average evolution of the vertical position and speed for a particular subject. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

## Tilt angle

As a reminder, the tilt is crucial since it strongly impacts the torque. The tilt is estimated thanks to the 3-dimensional accelerometer, making the measurement during the movement blurred by the hand acceleration. The results are displayed in FIGURE 3.9. As we already observed, the torque load leads to an increase in the tilt. Nevertheless, the tilt in the static phase is close to zero, meaning that most of the torque is properly handled. As expected, the tilt remains close to zero during the whole lifting phase when no off-centered load is added.

The catch-trials only clearly differ for the T0 condition. It seems that a negative angle appears during the lifting phase. This angle may be due to a non-desired torque applied because of the influence of previous trials. Even though this tilt seems to appear during the lift, it is attenuated instantaneously during the static phase.

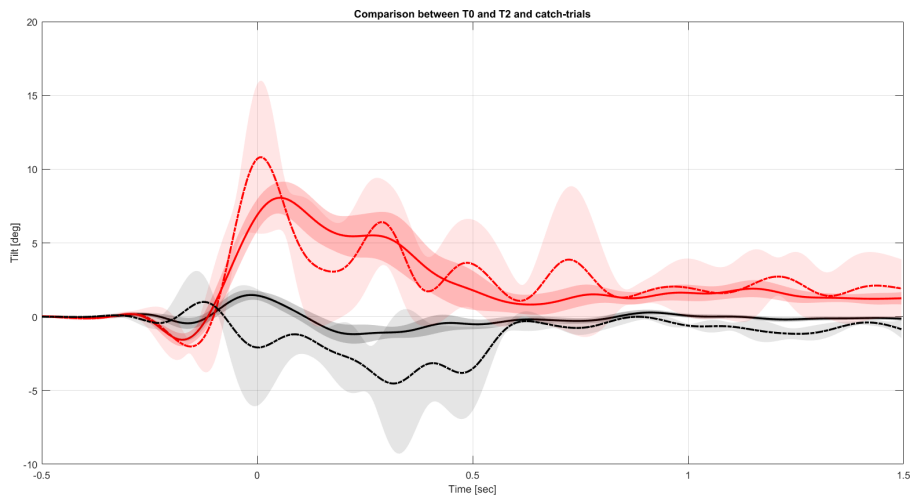


Figure 3.9: Average evolution of the tilt angle for a particular subject. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

## Grip force

The grip force is displayed in FIGURE 3.10, we will first focus on regular trials. The level of grip force is adapted with a higher grip force to handle a higher torque. The slopes of the increasing grip force also differ between the two conditions. For the no-torque condition, the maximum is reached at the beginning of the movement. On the other side, while manipulating the device with an off-centered mass, the grip force rises again slowly after the launch of the rising movement. This second rise is probably caused by the initial lack of grip force. This condition is not easy to counteract for some subjects and then applying this level of grip force requires effort and some time. The particularity is also that subject starts earlier to increase the grip force. The time at which they start pressing is supposed to be controlled with a sound signal, but we see that the torque condition will make them anticipate the pressure increase, only during adapted high-torque trials.

The catch-trials are very different from the regular ones. Beginning with the catch-trials with no torque following a high-torque block, we clearly see an overshoot in grip force. The grip force increases quickly, comparably to the high-torque trials before the movement begins. Just after the beginning of the rising movement, the grip force decrease slowly to catch up with the regular trial behavior. Before the movement begins, subjects are highly impacted by their memory while they do not have sensory information to identify the torque condition. As a consequence, the beginning of a catch looks like the previous adapted condition. But once they start

their acceleration, they benefit from a lot of information and then start to adapt to the actual condition. The high-torque catch trials seem to lack the anticipation present in the regular trials event though the grip force increases at the same speed. As a consequence, the grip force is lower at the beginning of the movement, and we see that the subject tries to catch up at the end of the movement, around 0.5 sec on the graph. The initial grip force, before the movement begins does not differ a lot from the regular trials, and is clearly different from the previous no-torque trials. The reason can be the visual information, in this case, described in the *Limitation and future work* section. Briefly, as we switch between a no-torque configuration and a torque-loaded configuration, the subjects visually see the difference in the setup. Even if we do not mention it, they immediately see the difference and anticipate the easiness of the future trial, which makes it not a true catch.

To summarize, the grip force seems to be adapted to the torque level. It is indeed the main control that we have on the manipulated object while holding it with only two fingers. Before the movement begins, the grip force is highly impacted by the previous condition through the starting time, the faster grip force rising, or the grip force level at the start of the movement. Once the movement started, the grip force is quickly adapted to catch up toward a regular grip force level. Unfortunately, the two conditions present visual differences that impact the catch. Typically, subjects do expect an easy movement when they recognize the T0 configuration, and a harder one when they see the off-centered mass.

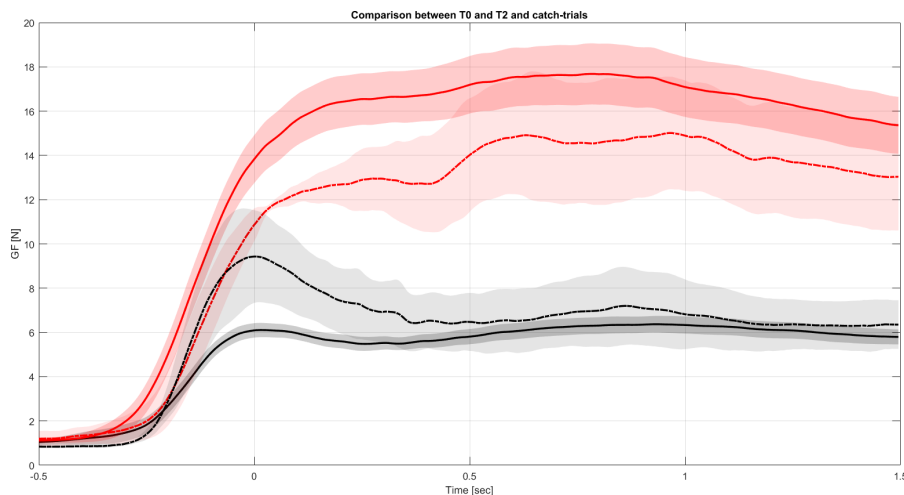


Figure 3.10: Average evolution of the grip force for a particular subject. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

## Torque

We have seen that the grip is adapted to the torque condition, and so is the kinematic of the movement. We could also see the influence of previous attempts on the catch-trials grip force behavior. But how do we adapt to the new condition? There must be some signals responsible for this fast adaptation, the torque can be one. The average torque measured can be seen in FIGURE 3.11 for each condition of interest. First, the torque level is strongly impacted by the torque load, meaning that the subject could properly counteract most of the torque.

Looking at T0 catch trials, we observe a great rising in the torque. Compared to a regular trial, this behavior is very different. This initial rising appears even before the movement begins, and must again be due to the subject's memory. Indeed this initial increase typically follows the high torque condition that precedes the catch. As we could also observe on grip force, the behavior changes just after the movement begins. The torque decreases quickly to get closer to an adapted trial. Nevertheless, the torque seems to keep a small positive value in the static phase that is not necessary. The behavior of the high-torque catch-trial is also consistent with the grip force we observe. We observe a typical pre-loading before the movement, comparable to an adapted trial. At this stage, the visual information impacts again the catch, and the subject expect a tough trial. Nevertheless, the memory of previous trials seems to have an impact on the torque. Right after the beginning of the movement, the torque decreases before a catch-up toward the regular behavior. The interpretation is that the subject is used to manipulate an object without off-centered mass, as he previously did a whole block with this condition. But first, the visual information tells him that the object has a torque load, leading to the pre-load behavior (starting -0.25sec). But once the movement begins and even though he was expecting the torque, his memory fools him and directly impacts his behavior by lowering the torque (around 0.1sec). But after some time, the sensitive information takes over the memory, and the subject adapts his behavior to the current torque condition (around 0.4sec). This shows all the information that influences the grip at some points. This information take over one after the other when our brain assumes they are the most relevant one among all of them. We see that the adaptation can be guided by different signals, and the behavior change appears very quickly.

The torque can be a signal that guides the grip adaptation. While manipulating an object with an off-centered mass, we feel the torque applied by this object and we can react to it. But is the torque sufficient to allow the adaptation? We observe for the T0 catch-trial that the torque can rise as fast and as high in a no-torque condition than in a high-torque condition. So a higher measured torque is not directly linked to a higher torque condition. Moreover, the interesting part is the beginning of the movement where we observe the adaptation step, between 0sec and

0.5sec. At a certain time in this step, we see the same behavior in both catch: the torque decreases. But after that, both have opposed reaction: the T0 catch-trial keeps decreasing toward the regular T0 level, while the T2 catch-trial completely changes its evolution to rise toward a regular T2 level. During this phase, the conditions are different and the torque decrease produces positive feedback in one condition and negative feedback in the other one. So if the torque may be a relevant signal to determine the current condition, it appears that it does not seem sufficient to distinguish all the conditions, especially regarding catch-trials.

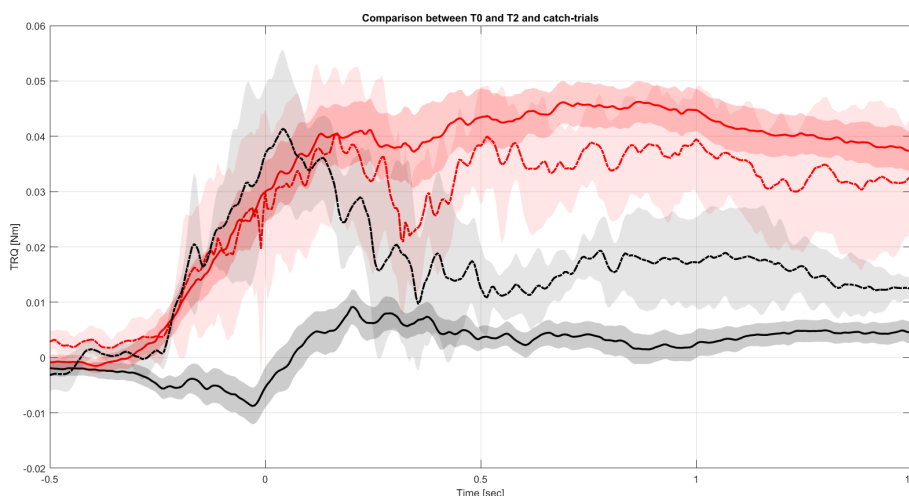


Figure 3.11: Average evolution of the tangential torque for a particular subject. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

## Strains

One idea of this study is that the fingerpad deformation is an informative signal used by the brain to understand the conditions of the grip. Strains are observed using a camera that captured the fingertip during the experiment. First, we must manually define the contact area of some images from the videos. Defining this area at any time is crucial since it changes a lot during the experiment when the finger slips or rolls on the glass. With the image sample that we manually made, we can get the contact area of the whole set using a deep learning algorithm. Data from this camera are then analysed with a 2-dimensional triangular mesh. Each triangle is defined by three vertexes with varying positions across time. Each vertex is a particular point that will be tracked during the experiment. Finally from the deformations of these triangles, we can compute the strains in two dimensions

and the shearing. Results are shown with a color scale, from dark blue for a high expansion to dark red for a high contraction.

An example is shown in FIGURE 3.12. The observed parameter is indicated over each picture while the torque condition is written on the left. We compare two conditions that show clear differences. The no-torque (T0) condition shows linear deformation in both directions. The horizontal deformation is a pure expansion, resulting from the compression in the normal direction, that we do not observe here. In the vertical direction, we see a compression area and an expansion area typical of a vertical load. The high torque (T2) condition shows a rotation deformation. The alternation of compression and expansion is typical behavior of a rotation, as the compression follows the finger ridges. We already see that the fingerpad deformations are highly impacted by the torque condition. Therefore, it could be a relevant source of information to evaluate the grip condition and engage the grip adaptation.

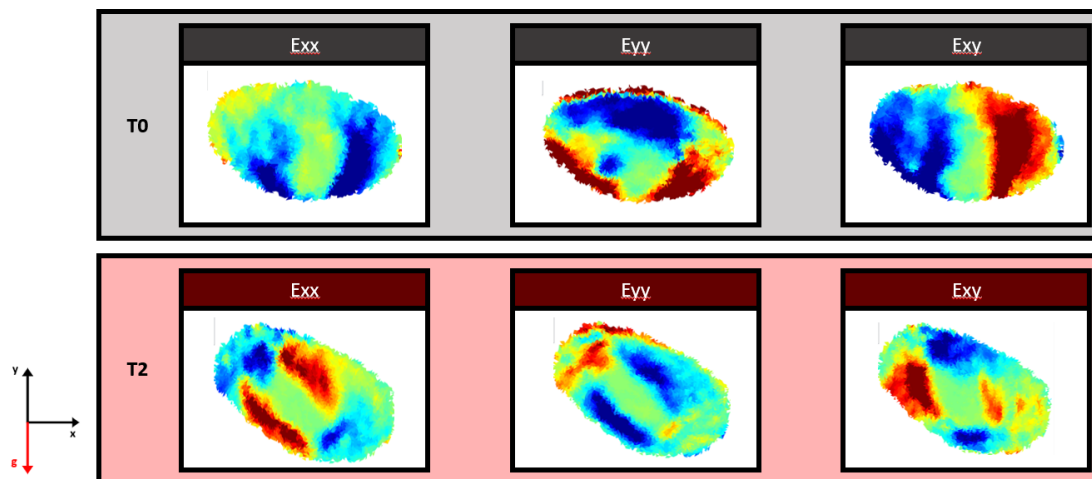


Figure 3.12: Strains in both direction and shearing of the fingerpad. Two torque conditions are represented : T0 and T2. The images are taken at the maximum load force of the trial and show the strain during one single frame. Results are shown with a color scale, from dark blue for a high expansion to dark red for a high contraction.

To make an easier comparison between the conditions, we decide to show the principle components of deformation instead of x-axis strains and y-axis strains. And we also show the curl instead of the shearing as it may be a crucial parameter in the analysis. We use this display to compare adapted regular trials and catch trials in FIGURE 3.13. The first noticeable difference is the finger angle. It seems that in adapted trials of the high torque condition, the subject changes his grip

to have an initial angle of the fingertip. The strains are also different during catch-trials even though it shows the same rotational behavior as regular T2 trial. It seems that the strain's division over the contact area differs from a regular T2 trial. In particular, the distal-proximal distribution is impacted, it seems that adapted trials use more the proximal part of the finger, while in catch the distal part is strained. Finally, the sticking part of the contact showing no strains in the middle seems to be reduced with an adapted trial with high torque, at the specific observed frame.

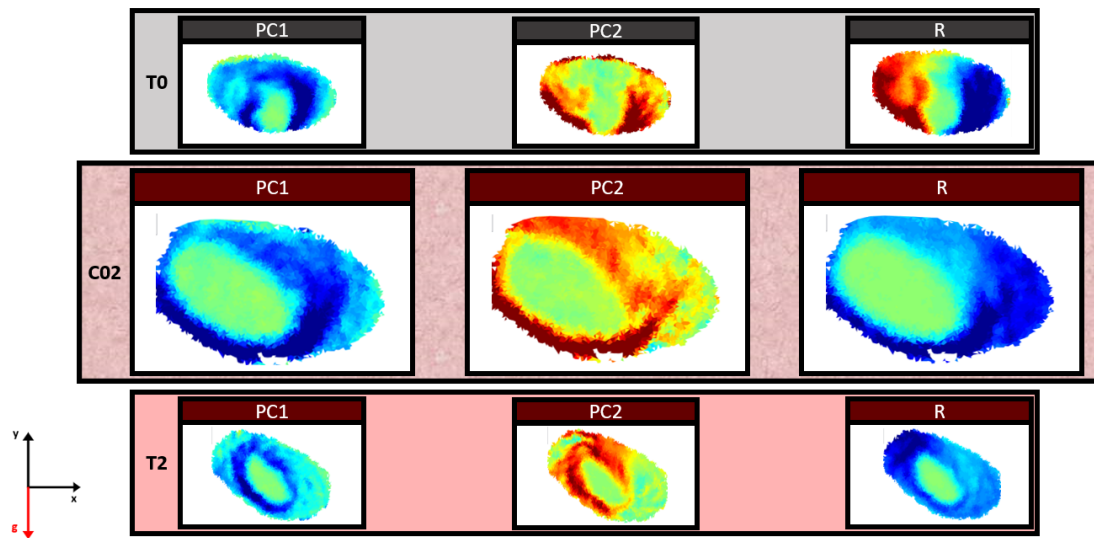


Figure 3.13: Strains in both direction and shearing of the fingerpad. We compare two regular condition and the catch trial from one to the other : T0 = adapted no-torque trial ; C02 = catch-trial from T0 to T2 ; T2 = adapted high-torque trial. The images are taken at the maximum load force of the trial and show the strain during one single frame. Results are shown with a color scale, from dark blue for a high expansion to dark red for a high contraction.

In FIGURE 3.14, we compare the same adapted conditions with the opposite catch. The catch trial shows a small rotation that should not happen in a no-torque condition. In general, the strain level seems to be much lower at this frame of the experiment. It does not mean that the linear strains are strictly lower, but strains may appear earlier or later, or even during a longer period.

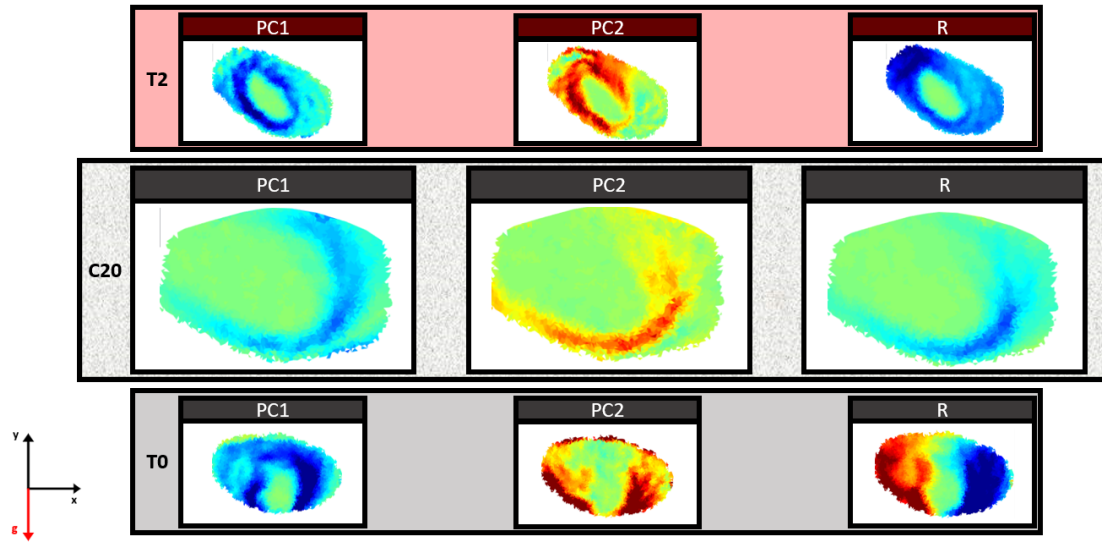


Figure 3.14: Strains in both direction and shearing of the fingerpad. We compare two regular condition and the catch trial from one to the other : T2 = adapted high-torque trial ; C20 = catch-trial from T2 to T0 ; T0 = adapted no-torque trial. The images are taken at the maximum load force of the trial and show the strain during one single frame. Results are shown with a color scale, from dark blue for a high expansion to dark red for a high contraction.

To study these results properly with averaged values over the different trials, we isolated two variables. The first one is the grip angle which means the estimated angle between the finger and the manipulandum. The second variable is the curl over the whole contact area at each time. The curl refers to the rotational movement of the fingerpad against the glass, and this particular movement is the biggest difference between a no-torque and high-torque load. Therefore, the curl level on the fingerpad could tell the brain that the manipulated object has an off-centered mass and even evaluate the torque intensity to adapt the grip at this particular condition.

Here, we show particular trials to try to characterise the behavior of the skin. More examples were observed and some of them are displayed in *Appendix B*

## Grip angle

The grip angle is estimated by fitting an ellipse to the contact area shape, as displayed in FIGURE 3.15. The ellipse angle is then computed, and we can observe its evolution through time, given a certain condition in FIGURE 3.16.

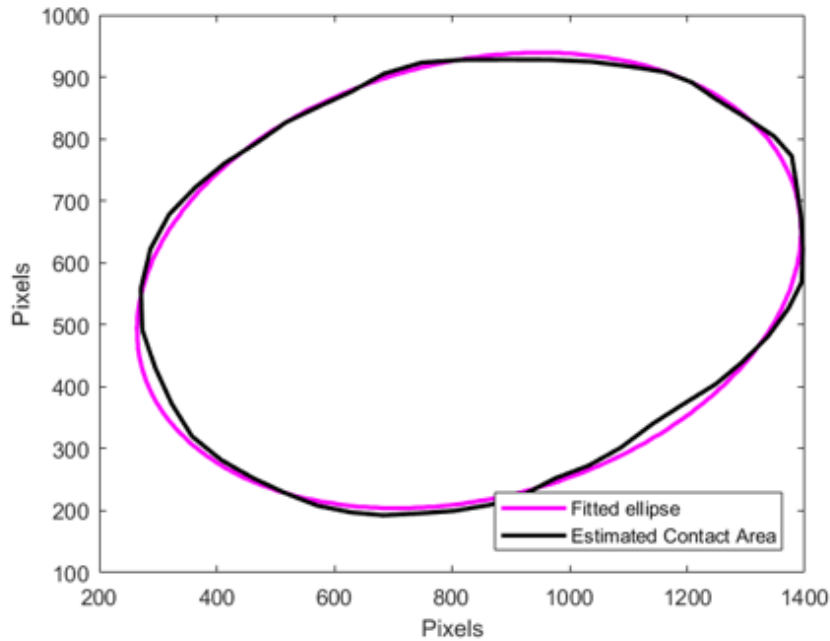


Figure 3.15: Fitted ellipse, in pink, to the estimated contact area of the finger, in black, on a particular frame

The grip angle varies depending on the torque condition. With no torque load, this angle remains stable during the whole experiment. When we add an off-centered mass, the finger will slip on the glass and rotate about  $15^\circ$  around the contact point. The catch does not seem to impact this angle dynamic, but only the starting value. In general, the chosen angle for a T0 trial is around  $-10^\circ$ . The same angle is used during catch-trials under the T2 condition after a T0 block. This choice leads to a positive angle at the end of the movement, which is to avoid in the experiment. As explained in the *Protocol* section, it is asked to the subject to avoid any other contact than the two fingertips, either with the hand or with the setup. In reality, a positive angle over about  $10^\circ$  leads to contact between the hand and the device or contact between the camera cable and the setup table. Both would make the results irrelevant and are therefore the highest priority event to avoid. The instructions and the particularities of the setup force the subjects that can not avoid slipping to add this initial angle for T2 trials. Doing so, the angle at the end of the movement is comparable with a T0 trial. The slip should not lead to any additional torque that would help the subjects to handle the torque.

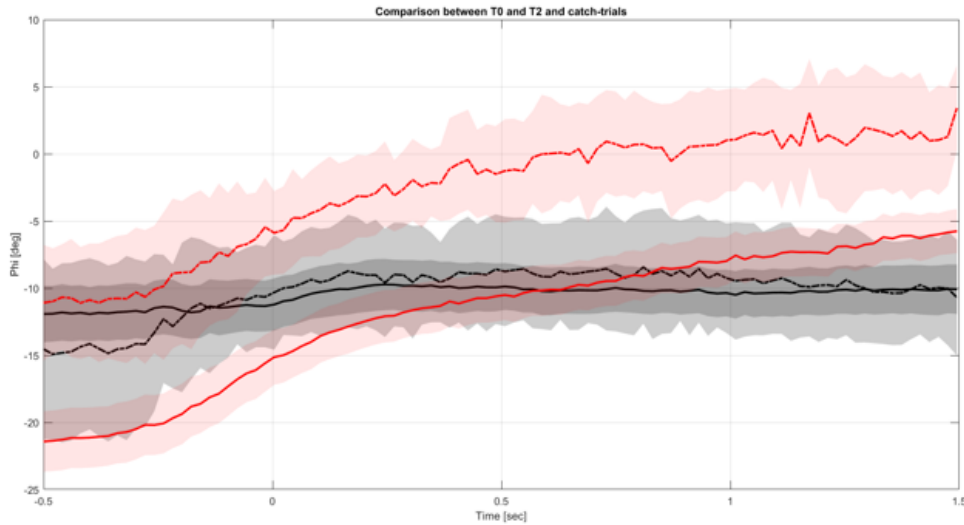


Figure 3.16: Average evolution of the grip angle for a particular subject. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

## Curl

The curl is a variable representing the deformation we are interested in. The purpose was to study the impact of fingerpad deformation on our grip adaptation while manipulating objects with an off-centered mass. In this particular condition, the torque created causes rotating deformation on the finger. This particular deformation can therefore be a signal to detect the presence of such off-centered mass and then initiate the adaptation. The curl is then a quantitative variable that measures the global level of this kind of deformation.

The curl is computed on each triangle that composes the mesh of the fingerpad. To analyse its global evolution, we sum all the curl at each time frame, weighted by the triangle areas. We end up with an estimation of the total rotating strains on the fingerpad at each time frame. The result is displayed in a graph in FIGURE 3.17.

The analyse starts with the regular trials in full line. As it was expected, the curl in a no-torque condition remains close to zero during the whole experiment. It confirms that the curl is a good idea to study pure rotating deformation, typically due to the presence of an off-centered mass. On the other side, the curl increases a lot in the T2 condition. It seems to increase until the launch of the lifting movement, while during the movement the curl keeps being positive but decreases. In the static phase, the curl reaches an almost zero value, confirming again that the subject handles most of the torque.

We look now at the catch-trials as we want to complete the first analysis based on torque measurement. The T0 catch-trial shows an increase of the curl during the pre-load. This curl increase follows the evolution of the previous condition, until dissociates and starts to slow down. The adaptation of the curl happens before any adaptation of the torque. Indeed, at the time the torque begins to adapt, the curl is almost already zero. The slow down of the curl may be due to the too high grip force and torque while it is clearly not needed. The sensitive information that the curl is decreasing can be the missing signal to distinguish the current torque condition. Indeed, while looking at the torque, the differences between T0 and T2 catch trials during the early movement were almost unnoticeable. Nevertheless, the torque could be adapted at some point, and the responsible signal can be the curl. At that time, when the torques in catch-trials start to behave oppositely, the curl is different in both cases. The curl could therefore be the original signal responsible for this opposite behavior in these two conditions.

To confirm that the curl is directly linked to our control, we can observe the time derivative of the grip force in FIGURE 3.18. We see a strong correlation between the curl signal and the evolution of applied grip force. In particular, we see a catch-up for T2 catch-trials after it decreased too fast in curl. It corresponds to the catch-up of the torque as well as the increase of grip force around 0.5sec.

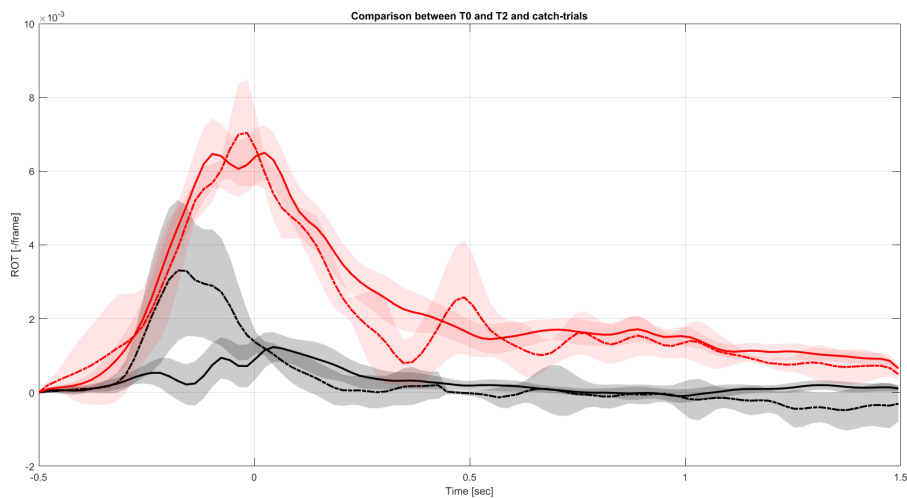


Figure 3.17: Average evolution of the curl over the whole contact area for a particular subject. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

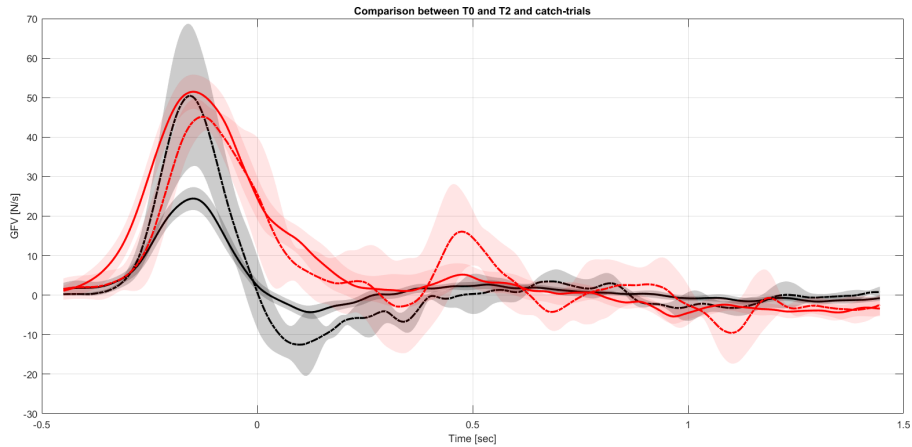


Figure 3.18: Average evolution of the time derivative of the grip force for a particular subject. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

### 3.3 Generalisation

In this section, we look at the variance between different subjects. Subjects' behavior varies depending on their strength, their ability to learn, or even the coefficient of friction between their fingers and the glass. So far we analysed mainly one single subject but he may not be representative of the majority of people. We also look at the low torque condition T1 and compare it with the T2 trials which are visually identical. We want to observe a clearer catch than we did with T2 catches compares to T0 trials. The graphs of every subject, and on average, for the main variables are shown in the *Appendix A*.

#### 3.3.1 Other subjects

The first noticeable difference observed concerns the tilt angle. Some subjects may encounter difficulties to counteract the high torque because it requires good grip strength. Subjects that do not have that strength tend to let the tilt increase to lower the torque. We can observe that behavior by looking at the tilt in the static phase, and we compare it to the total torque level. This relation is displayed in FIGURE 3.19. First, we observe that the tilt for T1 trials is well limited between -1 and 1 degree while T2 trials go up to almost 5 degrees. In both cases, we see that a higher torque tends to lead to a lower tilt. Looking at extremes, the torque

measured for the highest tilt subject is almost half the torque generated by the subject that keeps the tilt the closest to 0.

Tilt remains low for all subjects in the static phase. Nevertheless, a small variation strongly impacts the torque needed. To compensate for their lack of strength, some subjects may let a small tilt appear to relax the stress in their hand. This tilt is maybe not easy to see from the subjects' point of view, and one could be satisfied with some degrees of tilt.

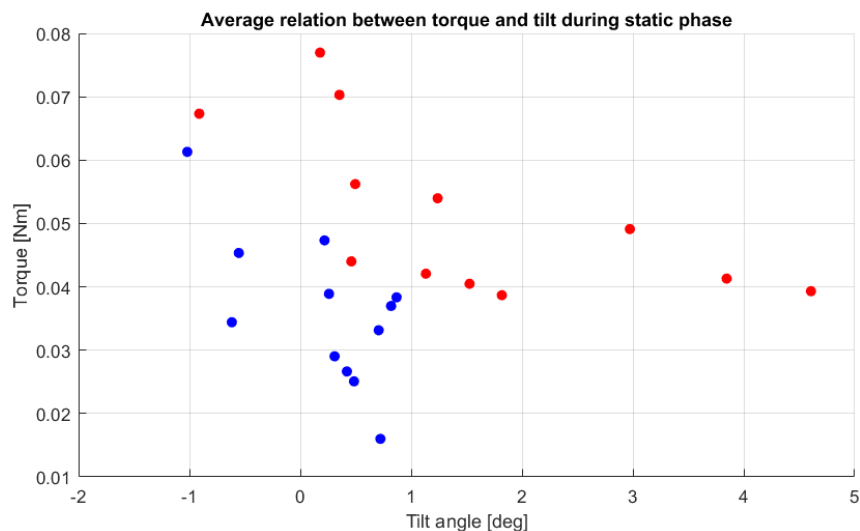


Figure 3.19: Relation between static torque and tilt. We plot the mean of each subject for the two loaded conditions. Blue dots for low-torque condition and red dots for high-torque condition

The main variable of interest in this study is the curl as it quantifies the fingerpad deformations. But the curl shows a lot of variance among the subjects. In FIGURE 3.17, the curl of our typical subject is high and conditions are clearly distinguishable. Unfortunately, it is not the case for any subject. On the other extreme, a subject has a relatively low curl on his finger, and conditions do not show clear differences. The results of this subject is displayed in FIGURE 3.20. This particular subject has strange data compare to what we expect, in particular, the maximum curl appears for the no-torque condition. After looking at the data, a link can be made with the torque level. This subject shows an extreme behavior in another measurement: the torque measured at the index. Even if its total torque is comparable to the average behavior of subjects, his torque applied by the index is very low. Until now we looked at the total torque by summing the torque measured on both fingers, but we have separated measurements for each of them. We displayed in FIGURE 3.21 the maximum torque measured at the index

regarding the maximum curl. As we observe negative torque for some subjects, the maximum norm of the torque was taken into account, whatever the sign. We observe a strong correlation between those two values. This result tells us that the measured curl on the index is probably not sufficient to make a global conclusion on the grip. We most probably miss a part of the information from the thumb. Capturing the thumb fingerpad is a priority to go further in this study, a more detailed analysis of this torque distribution is written in the *Limitations and further work* section, in *Torque distribution* paragraph.

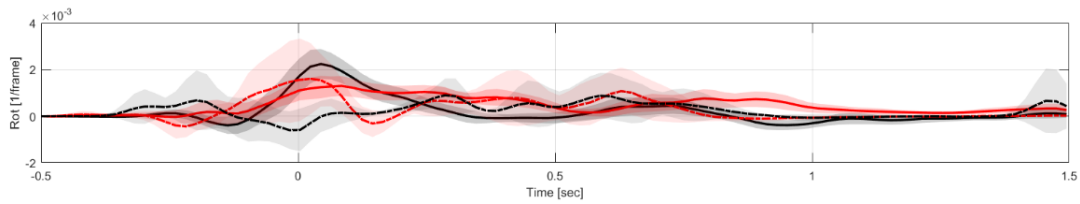


Figure 3.20: Average evolution of the curl over the whole contact area for a particular subject. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

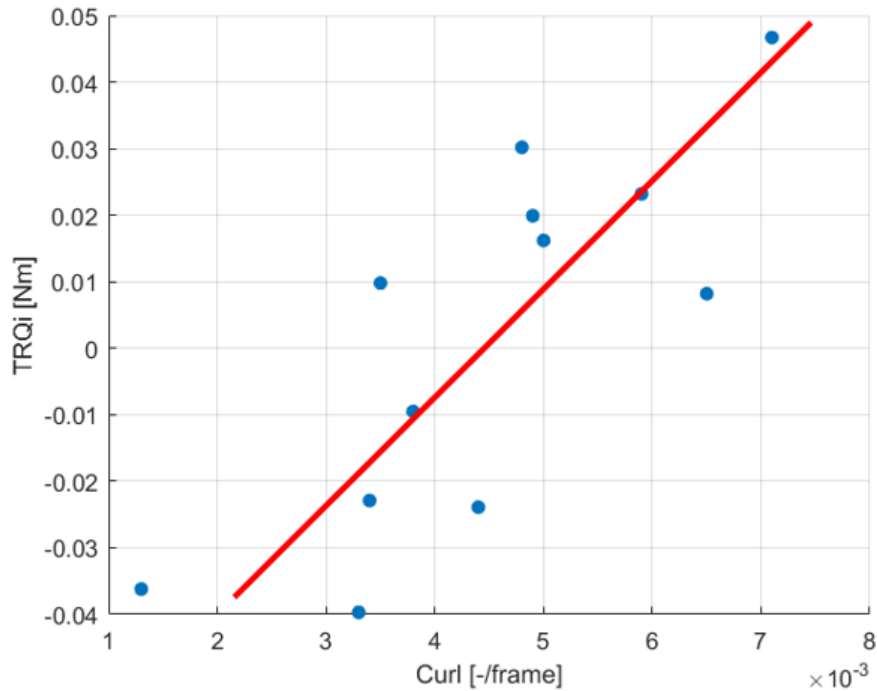


Figure 3.21: Relation between torque at the index and curl on index fingerpad. We plot the value with maximum norm of each subject for high-torque condition.

### 3.3.2 Different torque level

We already saw the general behavior of different torque levels in *Global results* section. In general, increasing the torque increases its effect. Therefore, higher torque implies higher grip force, higher torque, lower speed, and in general higher tilt angle. The original purpose of this study was to compare two situations: one with an off-centered mass and one without it. The benefit of this condition is that the subjects do not have any visual information, which is not the case when comparing with the no-torque condition.

Comparative graphs between the two torque levels for all subjects and in average are available in *Annex A*. Looking at these the conclusion remains the same. Catch-trials are still highly influenced by the previous condition and adapt during the movement.

# Chapter 4

## Discussion

### 4.1 Conclusion

#### 4.1.1 Torque impact

In this study, we can observe the general effect of an off-centered mass during active manipulation. The torque affects both kinematic and dynamic. The presence of torque leads to a slower movement. Slowing the movement limits the inertial torque generated by the vertical acceleration. This effect seems to be proportional to the torque level, as the higher the torque is, the slower the movement is. We also see a proportional adaptation of the grip force to counteract the torque. The required level of grip force to compensate for an off-centered mass is largely superior to a comparable centered mass. This grip force adaptation directly leads to a torque change. Grip force control is the main way to control the torque applied by the grip. Measured torque is directly imposed by the off-centered mass load. Nevertheless, during manipulation tilt angle can appear lowering the torque load. This tilt remains limited, as it is asked to subjects. But some subjects can not avoid tilt as they simply can not handle the full torque. As a consequence, they stabilise around some degrees where the torque is already noticeably lowered. This kind of behavior depends on the subject and can not be truly controlled, it is therefore considered as a kind of strategy to adapt their grip. Another kind of strategy implies the grip angle, which means the angle of the index relative to the manipulandum. Increasing this angle from the beginning allows a wider range of motion for the wrist. This is also a strategy that is adopted by subjects that struggle to handle the torque. As a consequence, undesirable slip occurs which we ask subjects to avoid as a top priority. The movement of the wrist allowed by this strategy can help to handle the torque for a short time but sufficient as part of this experiment. On the fingerpad, strains are strongly impacted by the off-centered mass. Without this one, the strains are linear and driven by the vertical load,

meaning the object mass. By adding off-centered mass, even small compared to the object's initial mass, the main deformations become rotation deformations. These deformations follow the shape of the fingertip, which is close to an ellipsoid shape. We quantify it by computing the curl over the whole contact area at any frame. The higher is the curl, the more we have this kind of rotating deformation, typical to the manipulation of an object with off-centered mass. On the other hand, without this mass, the overall curl remains close to zero as the deformation is mostly linear due to the vertical load caused by the object's own mass.

### **4.1.2 Catch-trials**

The second purpose is to study the impact of catch-trials. These trials are compared to the other ones, for which we observe an adaptation to the new condition. We have a satisfying amount of transitions to deduce a global effect depending on the previous condition. We observe that catch-trials are strongly impacted by the previous condition. The initial pre-load in particular presents a similar behavior as previously despite the condition change. This wrong pre-load can induce either overshoot and undershoot, depending on if we increased or decreased the off-centered load. At this step, subjects have no sensitive feedback to determine the current torque condition. Therefore, their behaviors are mostly ruled by the most recent experience they have, which is the previous block. When they start lifting the object, they start to adapt to the current condition. We clearly see that both grip force and torque go toward catching up with a regular adapted behavior. So even during the catch-trial, subjects start to adapt their grip to the new torque condition in less than a second. This adaptation is mostly possible thanks to sensitive signals, that allow a direct adaptation of the movement. This adaptation is so quick that it may not be intentionally controlled by the subjects. These results first emphasise the significant impact of the previous experience. This memory seems to rule the behavior of the subjects as long as they do not have reliable information to identify the current condition. The second main observation is the quick catch-up of the grip as soon as the subjects can feel the torque and the curl. The sensitive information takes over the memory to identify the force and torque requirement to handle the object load and allow a direct adaptation.

### **4.1.3 Informative signals**

The final purpose of this study is to identify the signals responsible for the adaptation of the grip. The two studied sensitive information are the torque and the curl on the index. The torque seems to be a relevant signal to distinguish two conditions when the subject is adapted. In this case, the torques are very different and therefore the level of perceived efforts in the fingers and the whole arm are very different.

Nevertheless, during catch trials the torque is also heavily impacted by the previous condition. In this particular case, the torque measured in both conditions is very similar, even during the early lift phase. But at some point, the subjects adapt anyway to the current situation, while the torque does not seem to be sufficient information to identify this current situation. The second signal, the curl on the fingerpad, is clearly distinguishable given the condition even in catch-trials. Indeed, even if the curl seems to be impacted by the previous condition, it seems to adapt faster than the torque. So when the torque is not relevant to identify the off-centered load level, the curl is relevant, because it has already adapted to the new situation. Both signals may be used in parallel to adapt the grip as both represent relevant information at some point. It seems that torque is not sufficient to adapt correctly to any situation. Even though the role of curl has not been proved, it seems to be a relevant signal to identify the condition and initiate the adaptation.

## **4.2 Limitations and further work**

There are a few limitations or non-idealities to this experiment. These were minimized with a minimal cost and using the setup as it was originally planned. Some parameters are not taken into account in this study despite our knowledge of their impact in this kind of experiment.

### **4.2.1 Visual information**

The first limitation concern the visual information that the subjects have that help them guess the torque condition in advance. The two different off-centered masses are visually identical, one being more full-filled than the other. These two conditions are therefore visually not distinguishable. Nevertheless, the no-torque condition is still different since the absence of off-centered mass is visible. Since that, subjects can anticipate the torque presence even during catch trials. Feedback from subjects tells us that even knowing that torque would increase or decrease, they were surprised during the movement.

The surprise when switching between torque and no-torque trial is then not a real surprise. To enhance our results, we can start by comparing the two identical conditions T1 and T2. These are not perturbed by visual information but study two different levels of torque which is interesting but does not lead to the same conclusion as comparing a torque condition with a no-torque one. To compare these without visual influence is not trivial. We could hide the whole setup from the subjects using a curtain but the control of the subject would be limited. The visual information is useful to avoid any non-desired contact or rectify tilt angle

that appears during the lifting phase, but study the behavior with a closed-eye variant could be interesting further work.

## 4.2.2 Torque distribution

The limitations related to the thumb are mainly due to the absence of visual data. We currently focus on the visual analysis of the index as it is the one captured during the experiment with the camera. It is also the easiest to observe as it is more regular than the thumb, mostly speaking about the contact area that can be tough to define. On the other side, we observe the total torque measured, summing the index and thumb ones. By linking the total torque level to the visual information of the index only, we assume that the fingerpad deformations on the thumb will follow the same behavior as the index.

As the shape of the thumb and index differ and the precision grip is not symmetric, it seems hard to believe that both fingers contribute at the same level to handle the torque. We can have a first look at it by looking at the measured torque on each side.

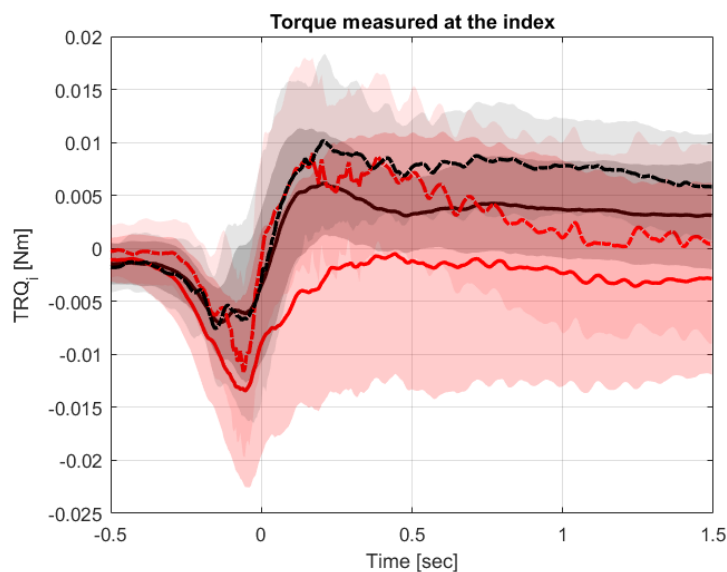


Figure 4.1: Average evolution of the torque at index for all subjects. We compare two levels of torques : T0 in black and T2 in red. Doted lines represent the catch-trials mean for the torque condition of associated color.

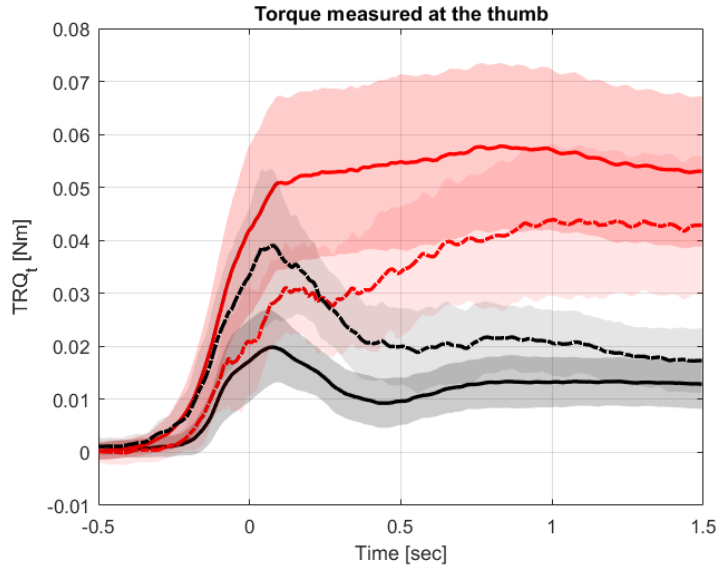


Figure 4.2: Average evolution of the torque at thumb for all subjects. We compare two levels of torques : T0 in black and T2 in red. Doted lines represent the catch-trials mean for the torque condition of associated color.

The torque distribution between index and thumb is displayed in FIGURE 4.1 and FIGURE 4.2. As we see on the two graphs, the torque induced by the thumb is much higher than the one from the index. Moreover, it seems that in the adapted high torque condition, the subjects lower the torque applied with their index. This torque even goes in the negative for some of them, meaning that it goes against the total torque. Because even if this can happen, the total torque of high torque condition is always positive and consistently higher compared to other conditions. This particular distribution is surprising but seems to be true for all subjects. We could explain it by the asymmetries of the grip. We already talked about physiological differences between the index and the thumb, but most probably they do not have the same role in the precision grip. For example, the position of the fingers is not perfectly symmetric on the glasses. We can think that losing some torque on the index is the price to pay to increase the total torque thanks to the thumb.

This observation confirms that we miss information to properly analyse our data. We could miss a clear relation between fingerpad deformation and torque by not having visual data of the thumb. Nevertheless, it does not mean that studying the index is irrelevant. Even if the index does not participate as much as the thumb to counteract the torque, it clearly reacts to the torque load. The index could even play a greater role in sensitive information while the thumb ensures mechanical function. Capture the thumb would definitely be a priority in the

future to complete this study, despite it is currently impossible to capture both fingers at the same time. But even though adapting the setup to allow that seems challenging, we can easily make a second experiment sample filming the thumb and complete the current data.

### 4.2.3 Friction and humidity

Two critical parameters that were not studied yet are humidity and friction. Both are linked since humidity level affects the friction coefficient between the finger and the device. During the experiment, we made a quick measurement of the forces while subjects are scrubbing the glass up and down with their index. This is performed at three levels of normal force. Doing so we can characterise the friction coefficient over a range of grip force because the friction coefficient varies with the normal force. This friction coefficient is crucial in the experiment because the friction is mainly what allows us to counteract the torque by increasing the grip force. So the three different conditions that present on average different levels of grip force would have different friction coefficients. Moreover, this coefficient varies among subjects. Furthermore, the moisture of the fingers impacts the friction and varies during the experiment. The grip force itself could be responsible for the moisture increase or decrease, thanks to biological mechanisms [11].

Further work could imply the analysis of friction coefficient variance between subjects, and its correlation with the rest of the data. If moisture comes to be a variable of interest, we should do more experiments while measuring the moisture of the fingers between the trials. Some currently inexplicable behavior of particular subjects may be caused by the moisture irregularities of these subjects.

### 4.2.4 3-dimensional study

Further studies may also be interested in studying the grip as a 3-dimension operation. Previous studies already mention the presence of in-depth deformation that we can not observe on the contact area [6]. Deformations occur perpendicularly to the contact and are also likely to be relevant information in the grip control.

Moreover, the two-finger precision grip is intuitively not the best option to handle a tangential torque. Studies on a 3-degree-of-freedom skin deformation feedback made experiments with a 3-finger grip where subjects had to determine the location of a contoured hole [12]. They compared 1-DoF and 3-DoF deformation feedback and observed better performances with the 3-DoF, indicating that the subjects are able to interpret the multi-DoF force information provided by a sensory device. It would confirm that the 3-dimensional aspect of the grip is critical in our adaptation process. We can expect to observe a similar or even higher impact with an off-centered mass.



# Appendix A

## Graphs

### Subject 1

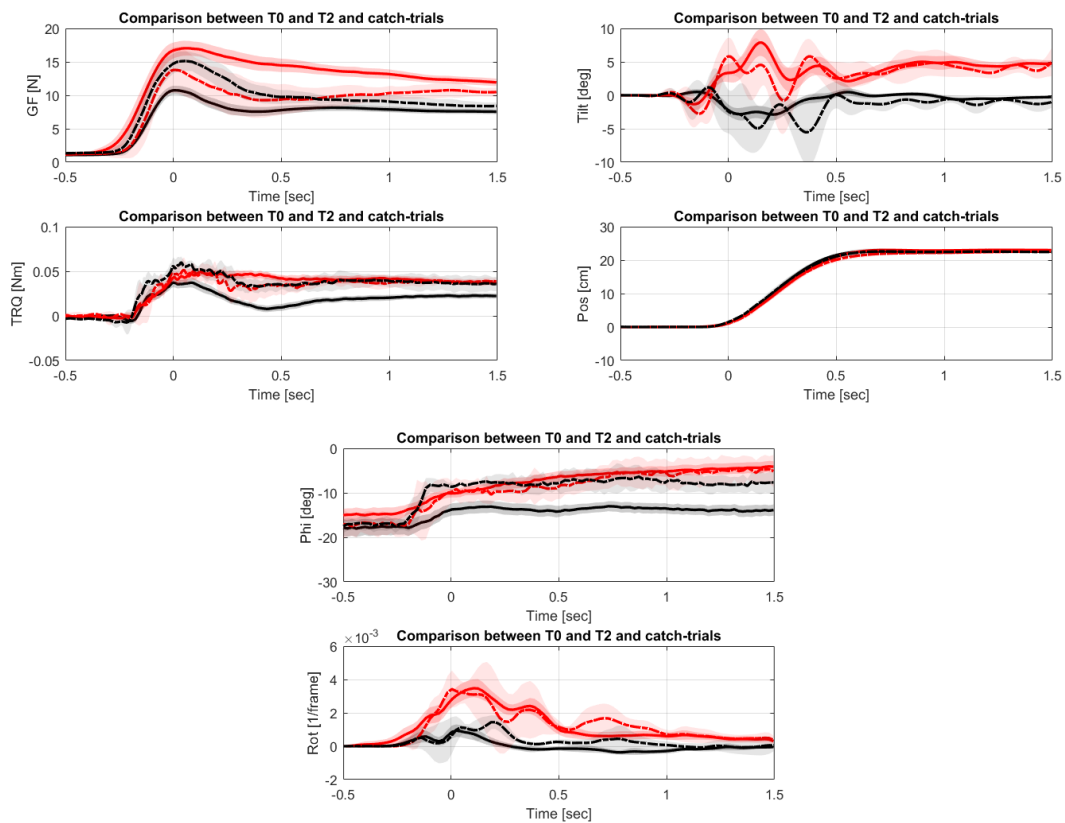


Figure A.1: Average evolution of the main variables for subject 1. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

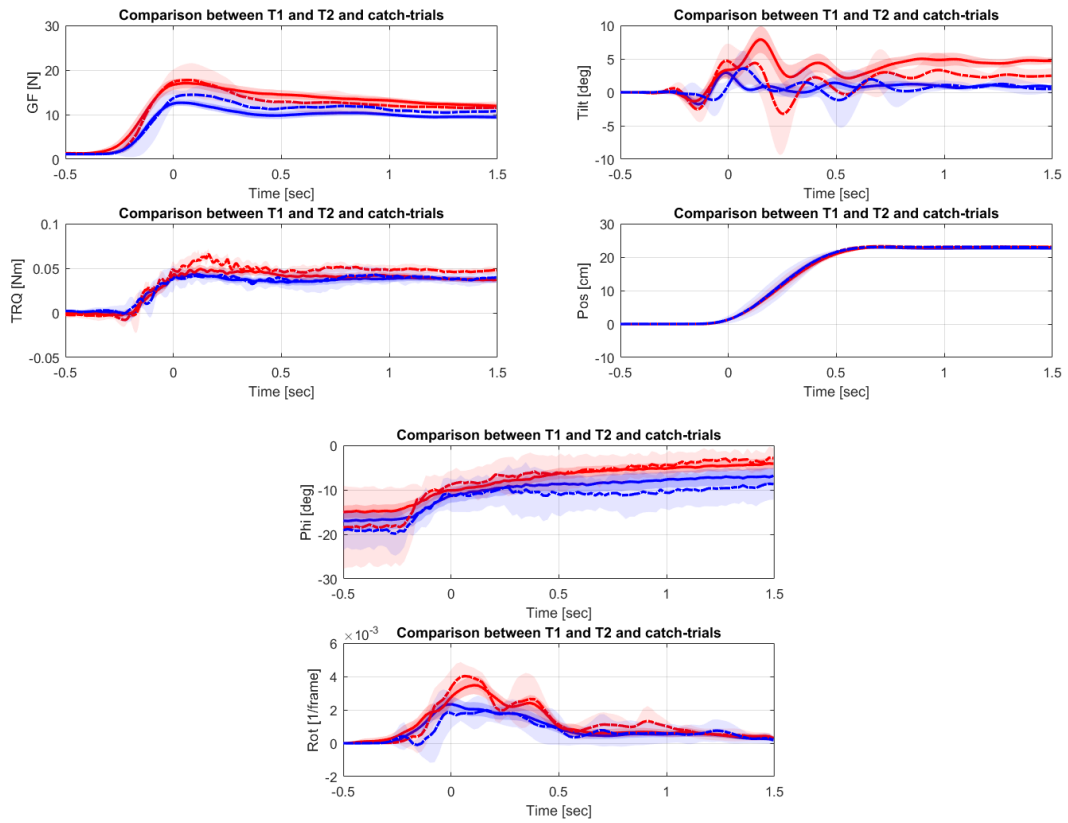


Figure A.2: Average evolution of the main variables for subject 1. We compare two levels of torques : T1 in blue and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

## Subject 2

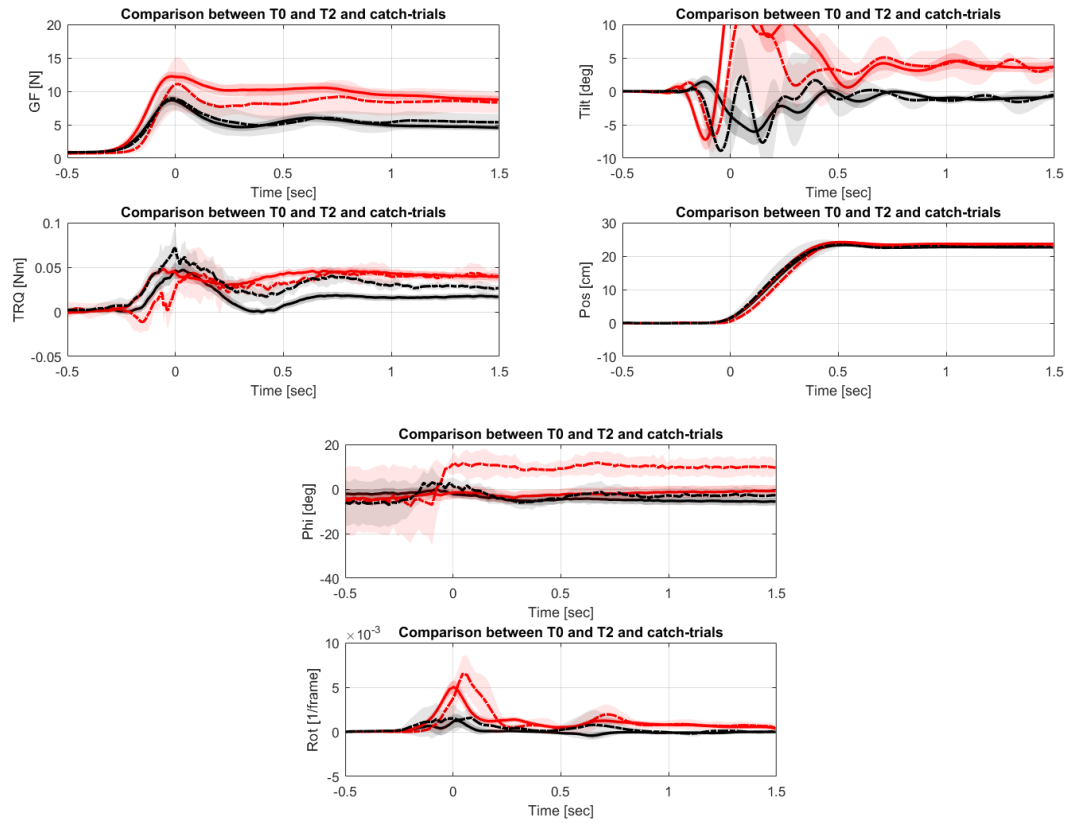


Figure A.3: Average evolution of the main variables for subject 2. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

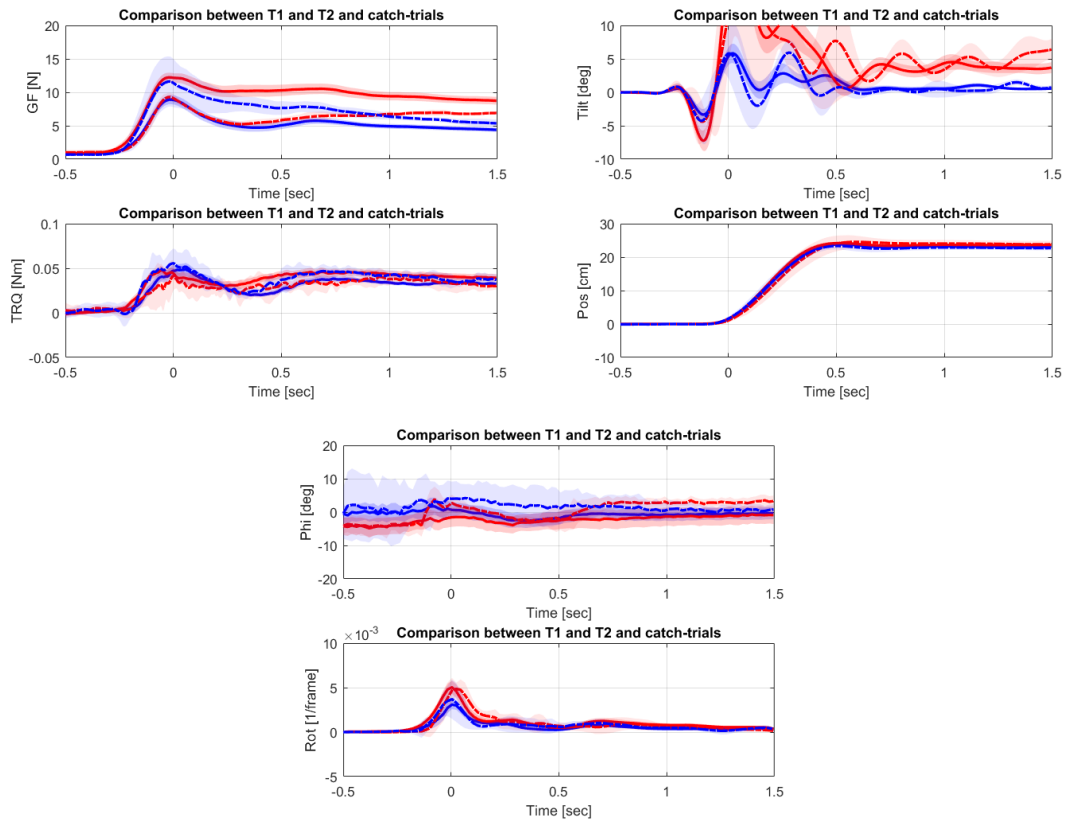


Figure A.4: Average evolution of the main variables for subject 2. We compare two levels of torques : T1 in blue and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

## Subject 3

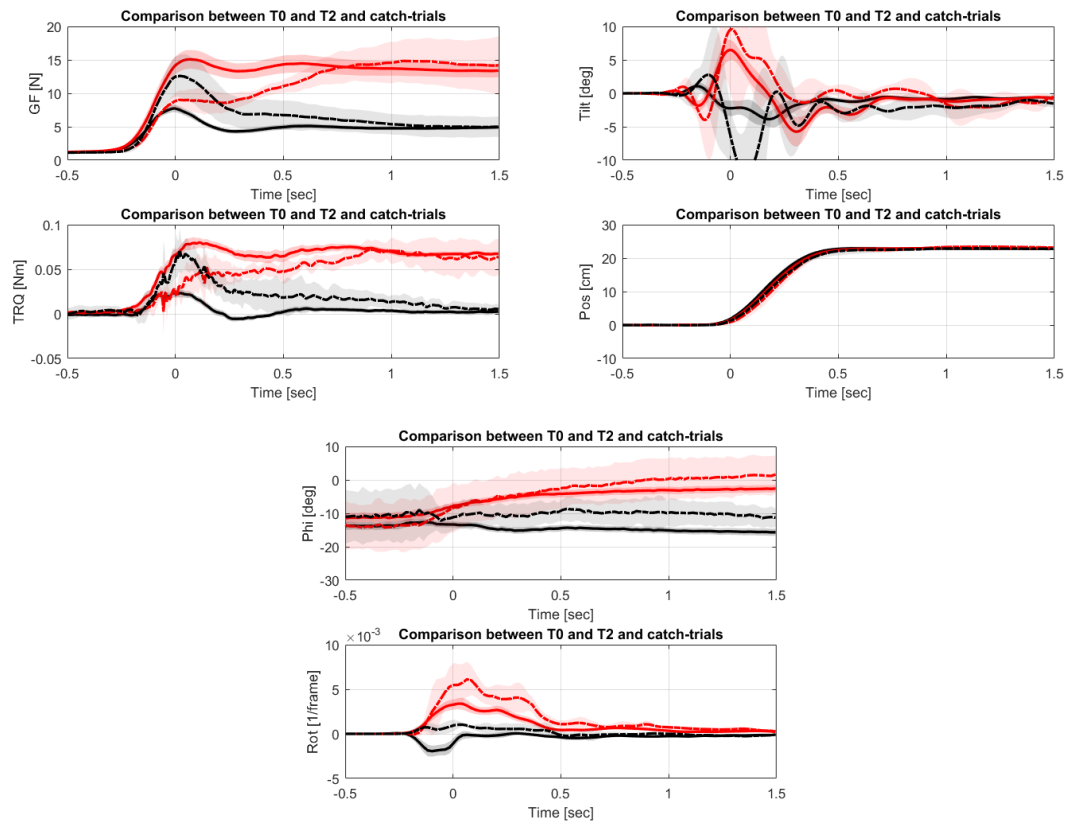


Figure A.5: Average evolution of the main variables for subject 3. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

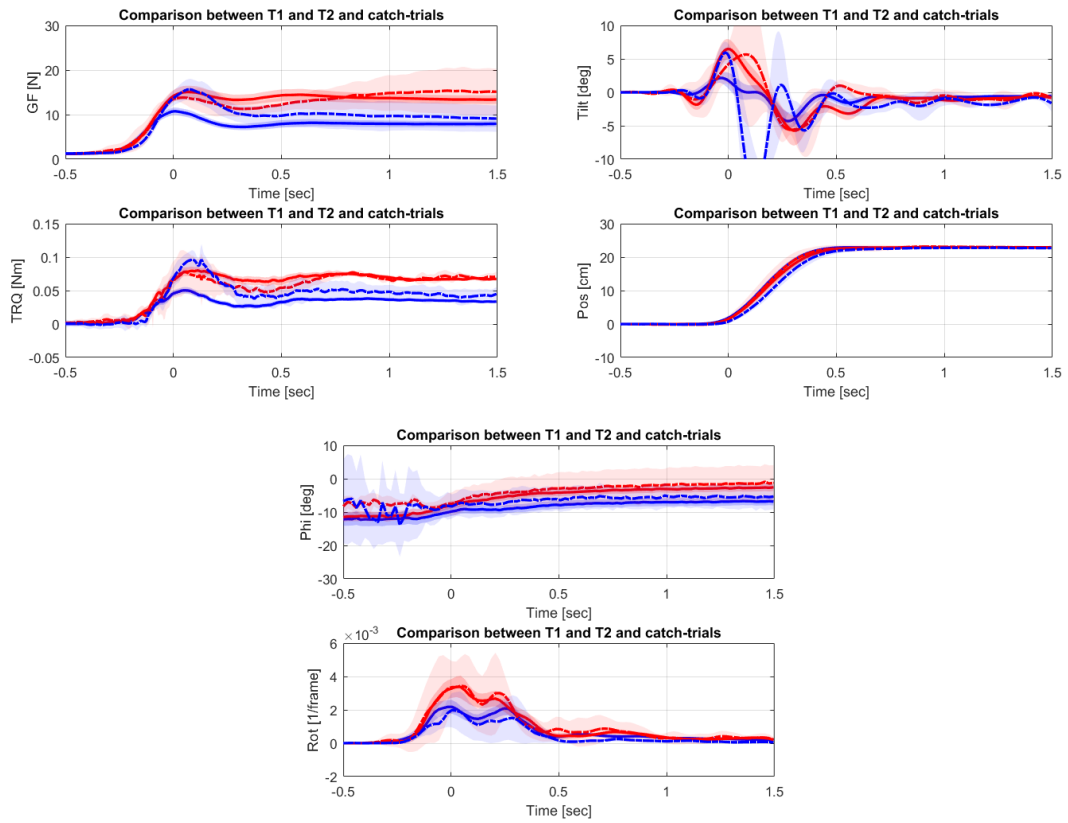


Figure A.6: Average evolution of the main variables for subject 3. We compare two levels of torques : T1 in blue and T2 in red. Doted lines represent the catch-trials mean for the torque condition of associated color.

## Subject 4

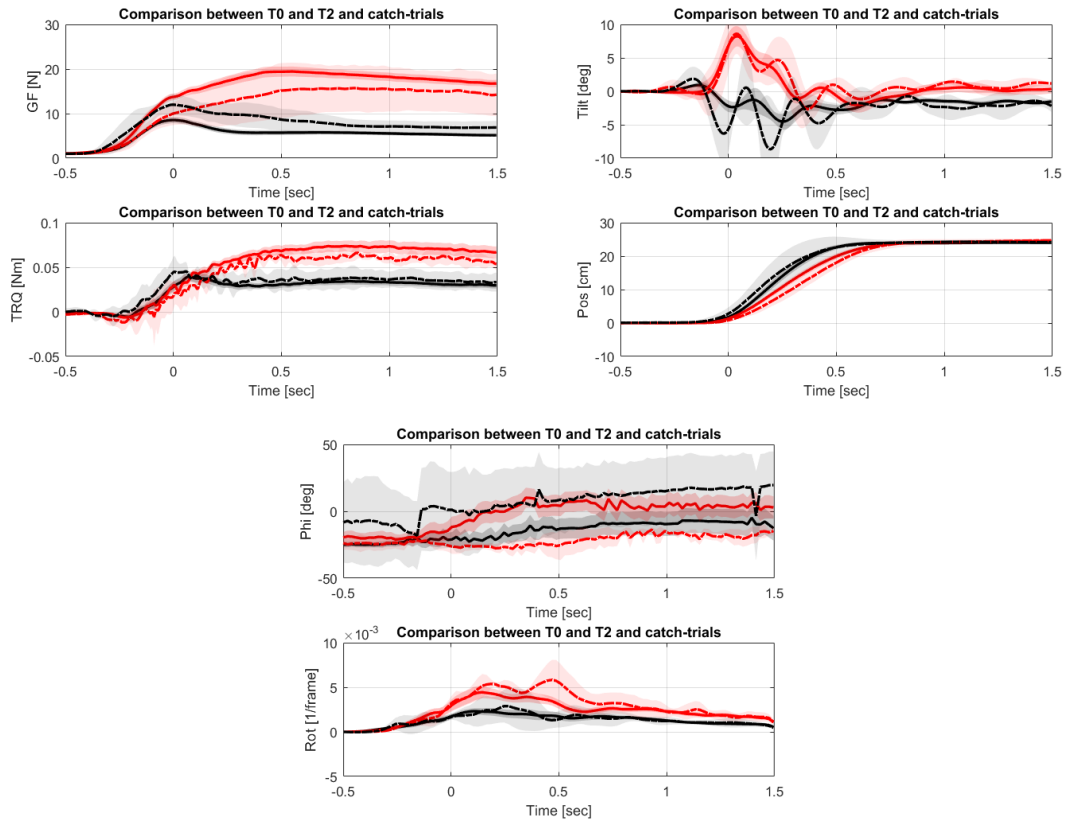


Figure A.7: Average evolution of the main variables for subject 4. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

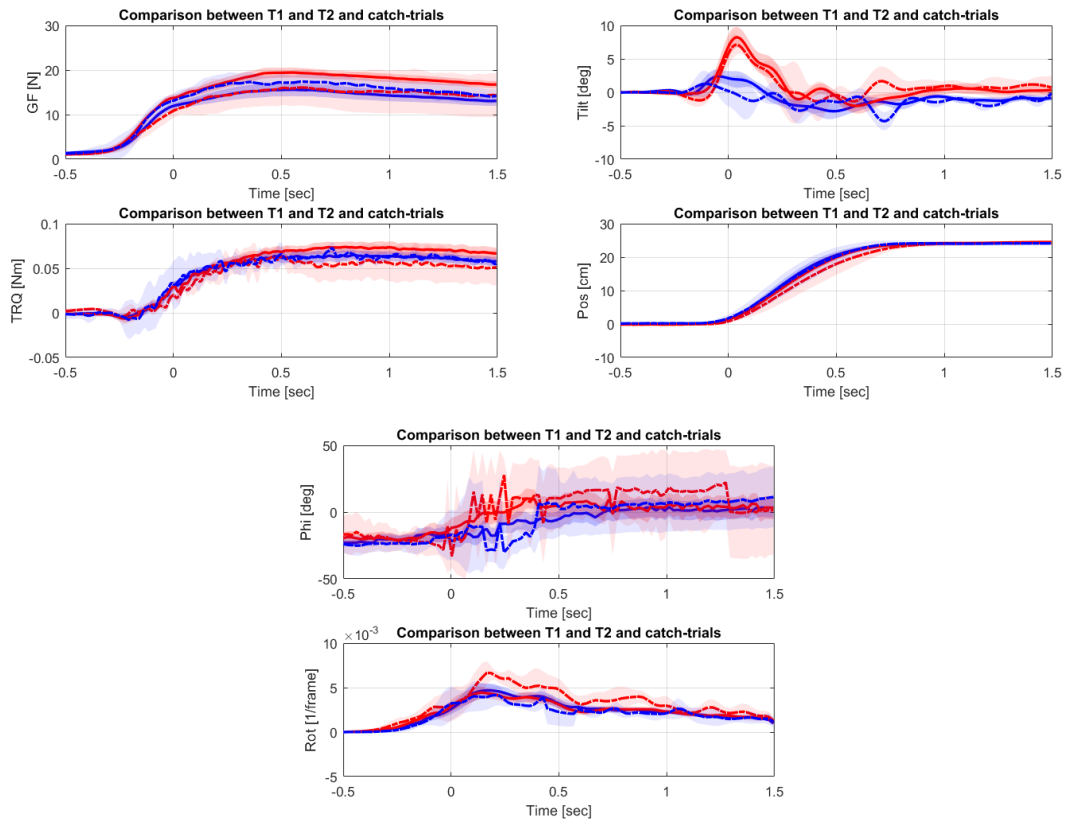


Figure A.8: Average evolution of the main variables for subject 4. We compare two levels of torques : T1 in blue and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

## Subject 5

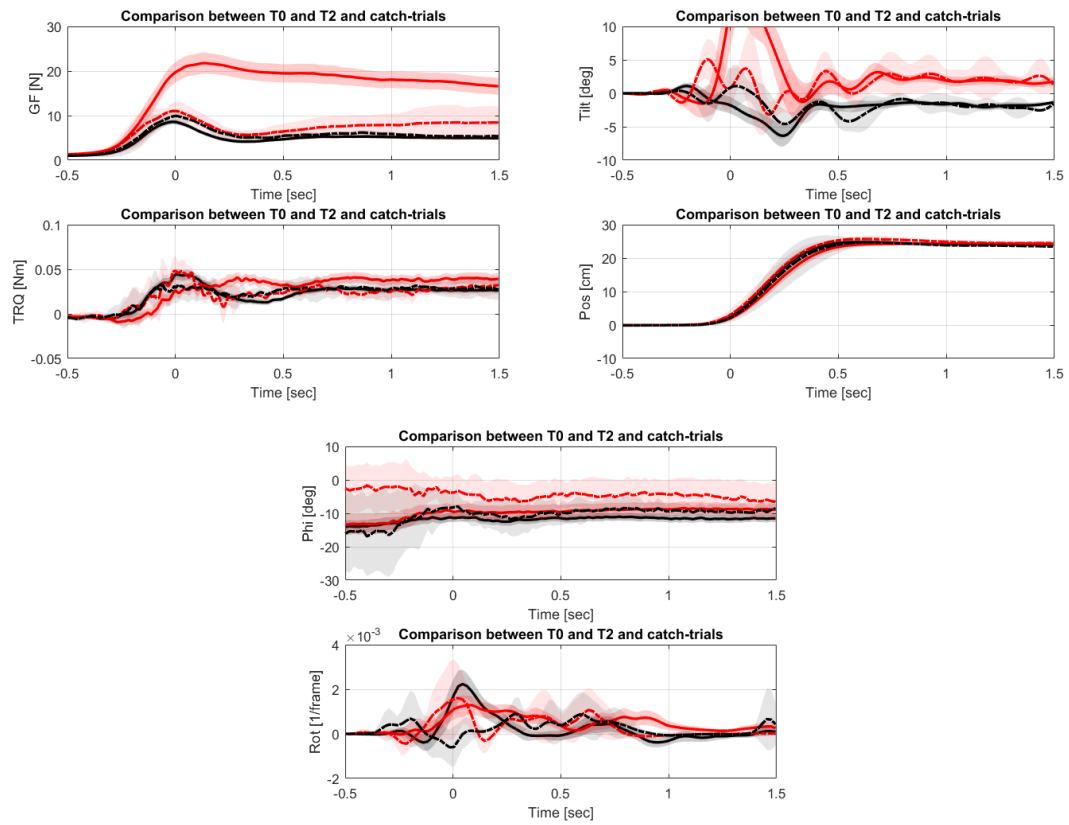


Figure A.9: Average evolution of the main variables for subject 5. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

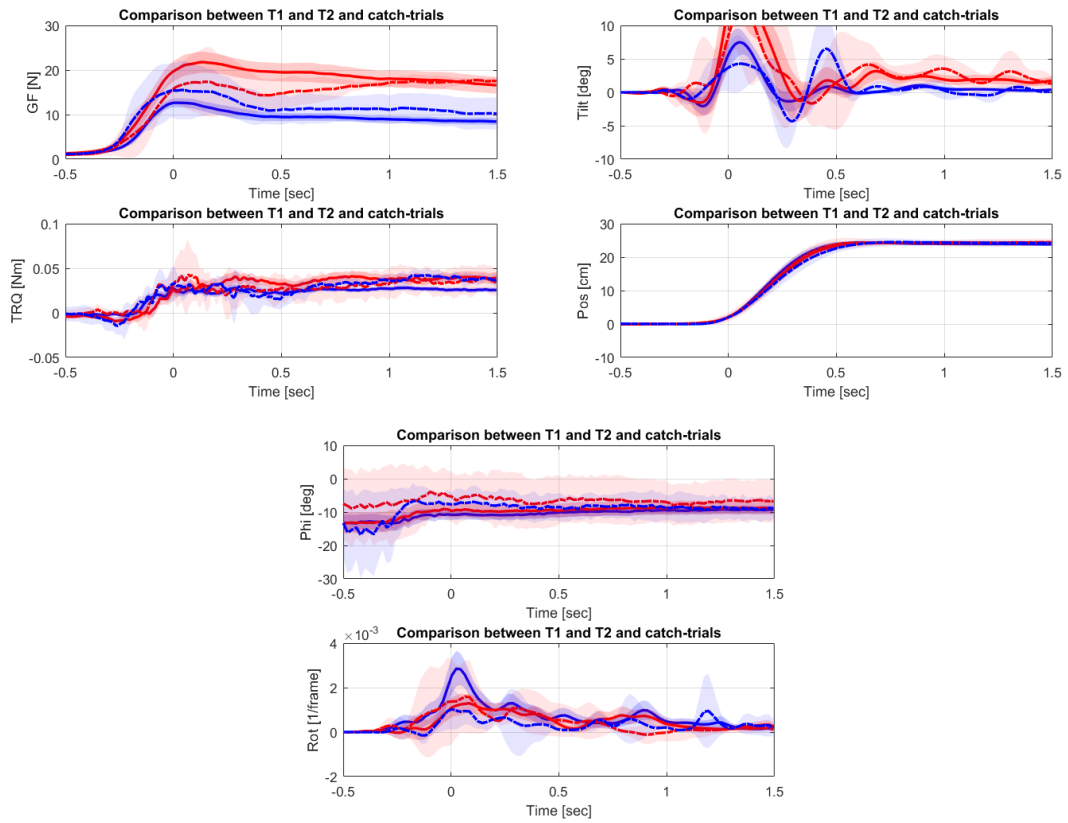


Figure A.10: Average evolution of the main variables for subject 5. We compare two levels of torques : T1 in blue and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

## Subject 6

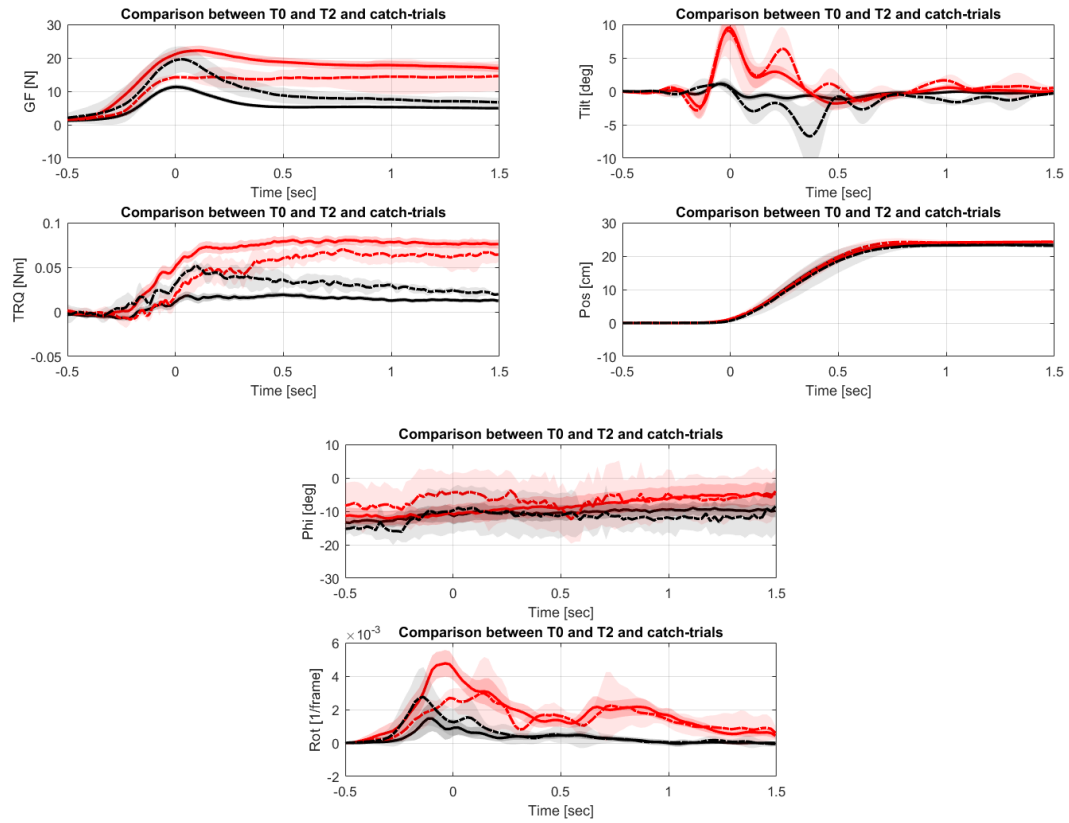


Figure A.11: Average evolution of the main variables for subject 6. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

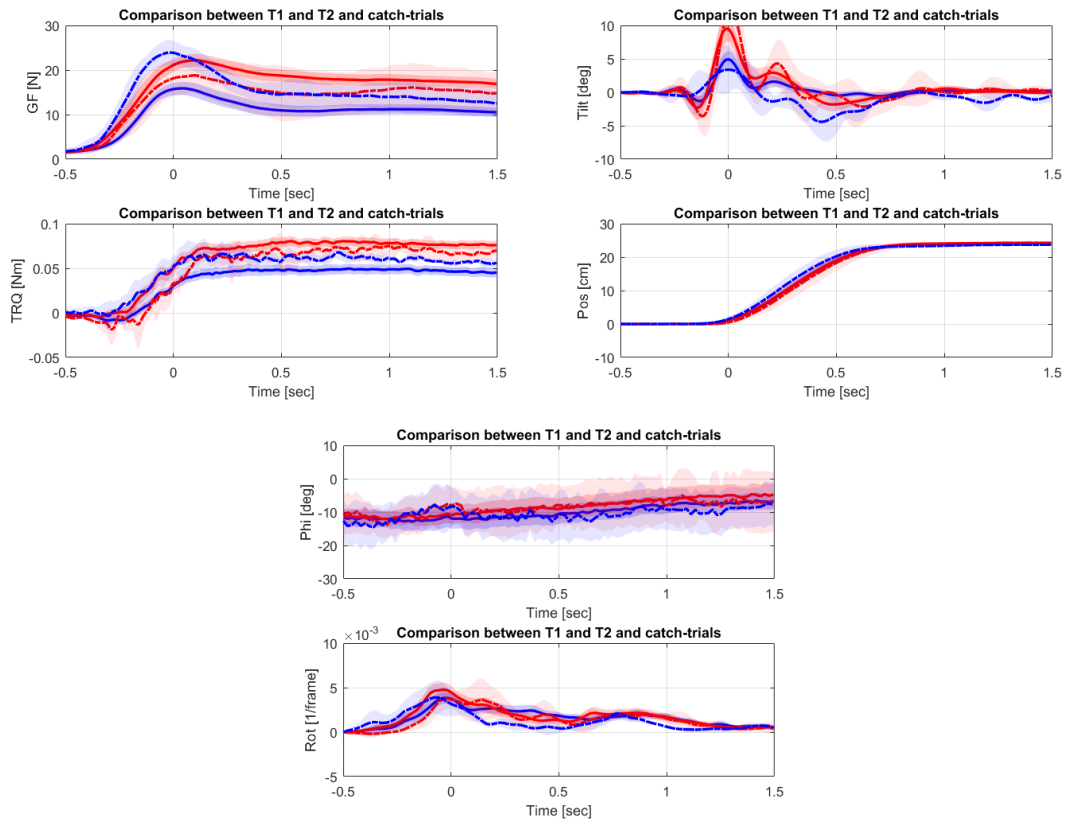


Figure A.12: Average evolution of the main variables for subject 6. We compare two levels of torques : T1 in blue and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

## Subject 7

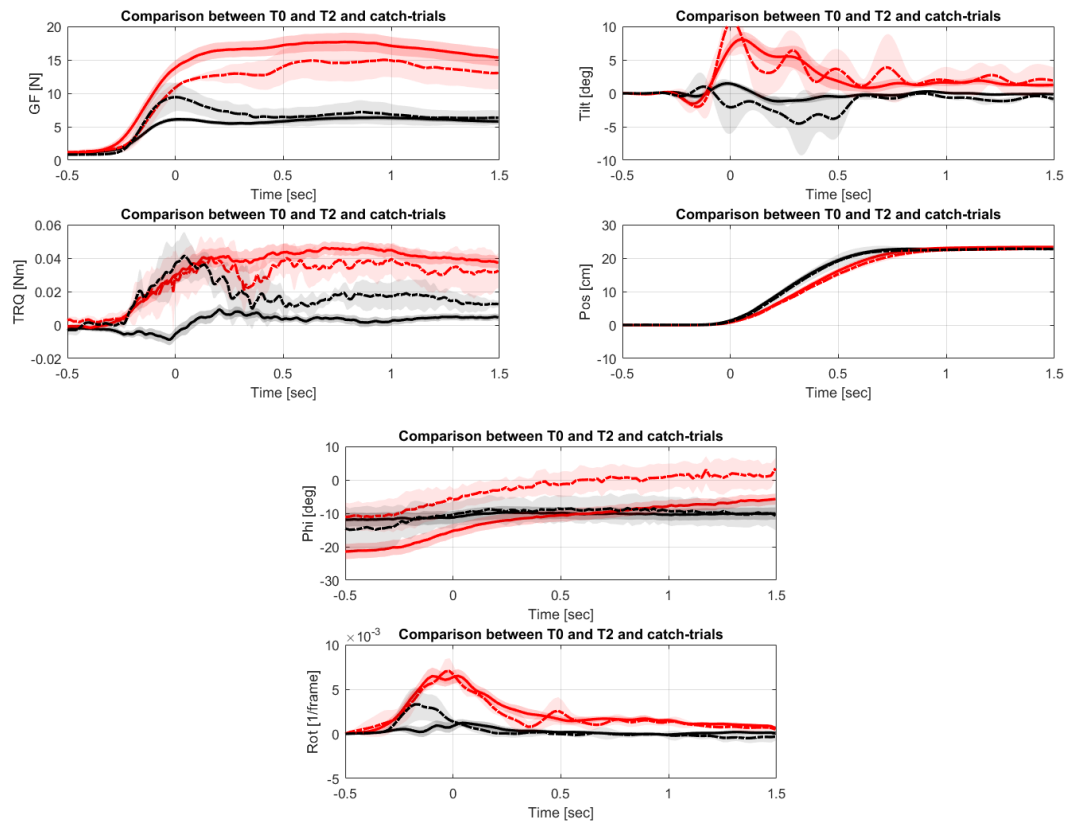


Figure A.13: Average evolution of the main variables for subject 7. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

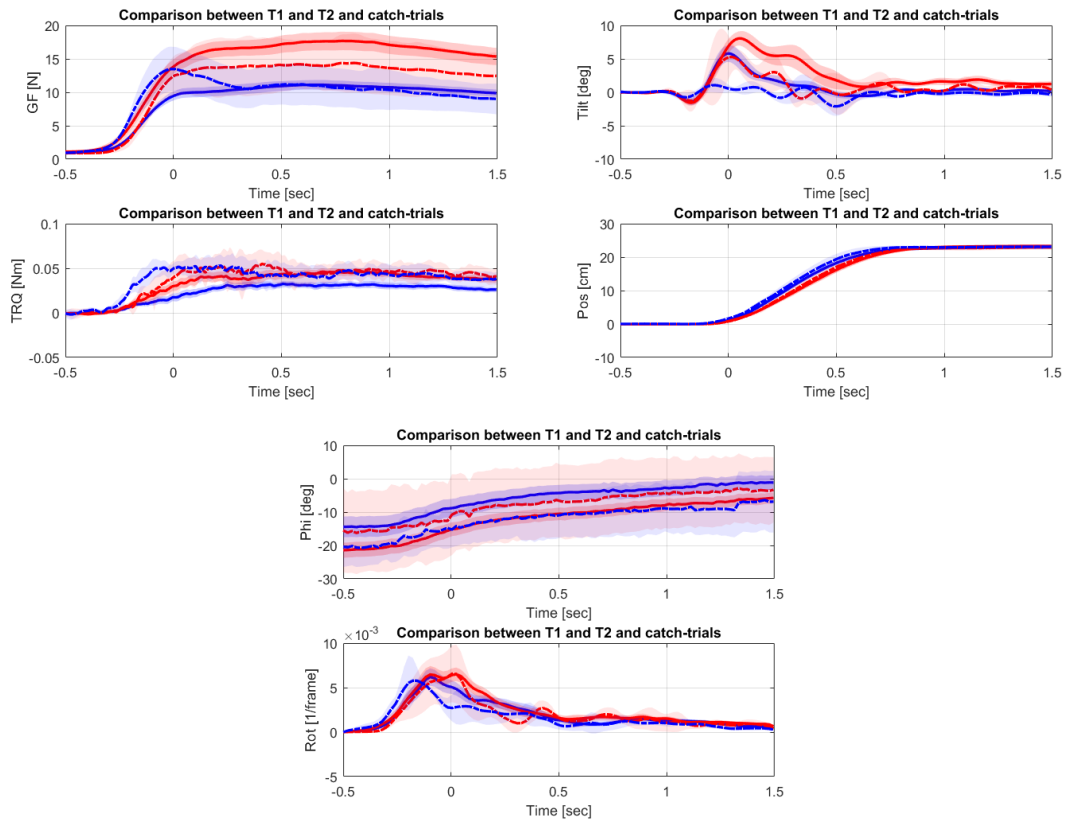


Figure A.14: Average evolution of the main variables for subject 7. We compare two levels of torques : T1 in blue and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

## Subject 8

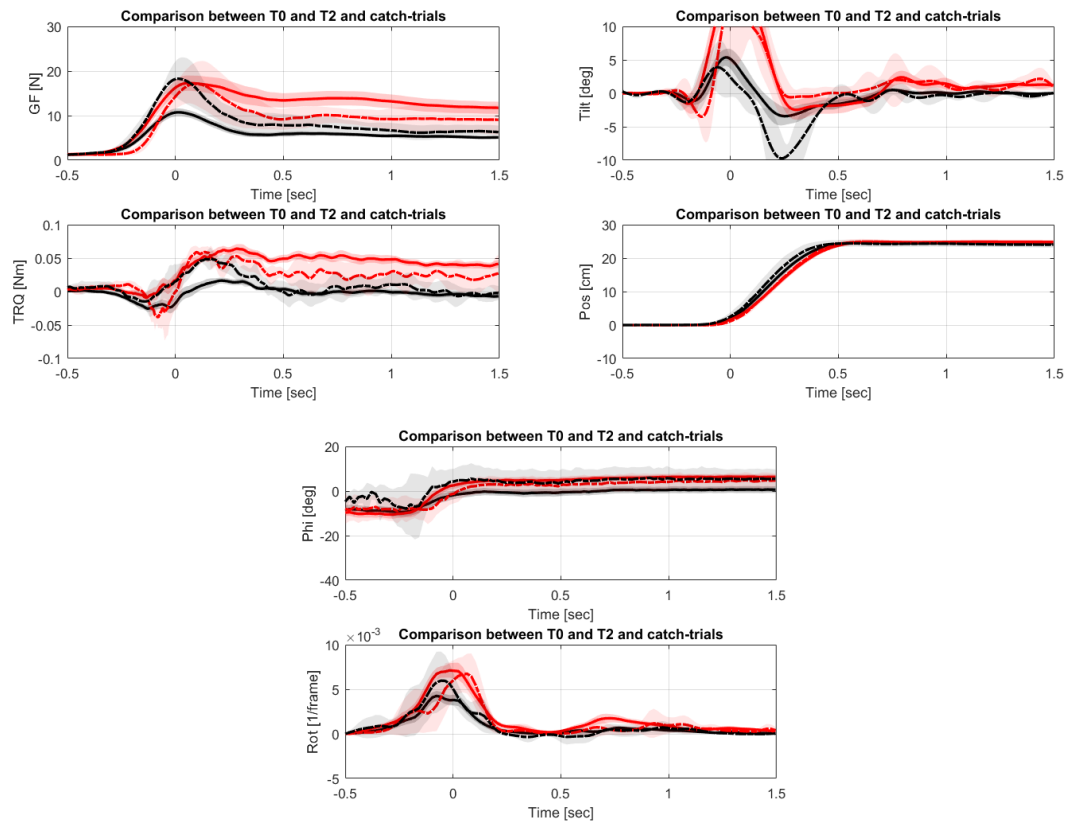


Figure A.15: Average evolution of the main variables for subject 8. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

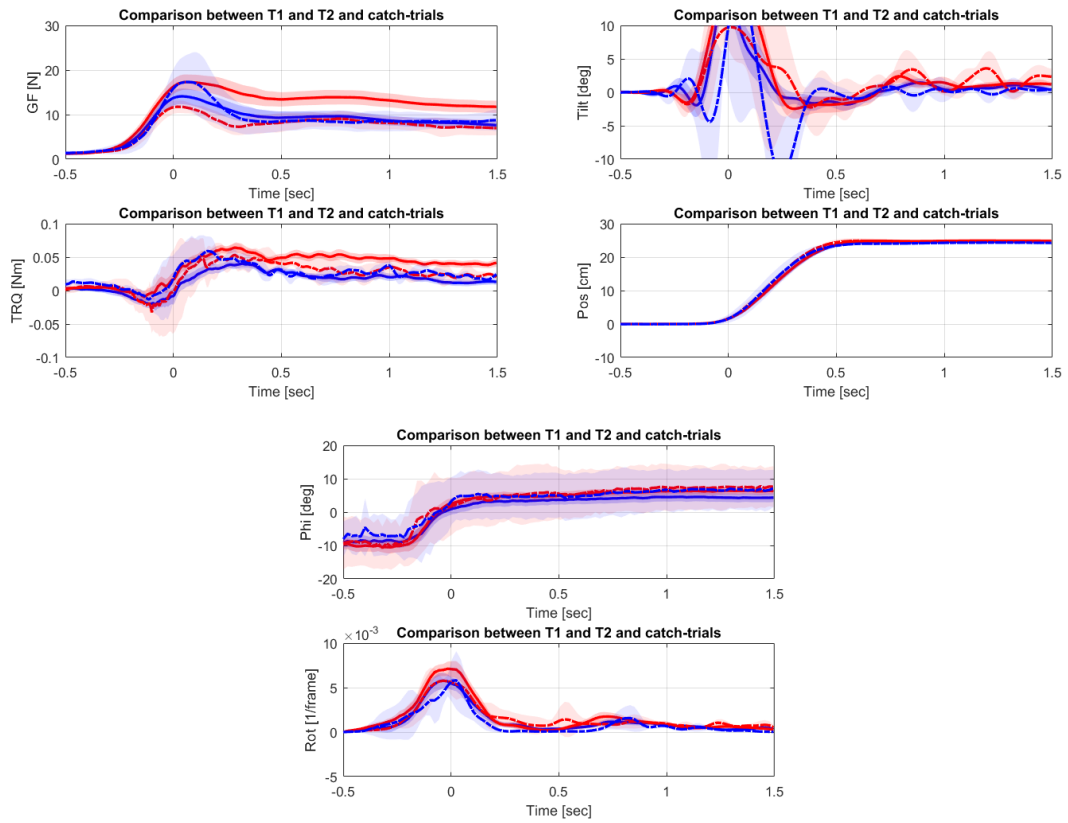


Figure A.16: Average evolution of the main variables for subject 8. We compare two levels of torques : T1 in blue and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

## Subject 9

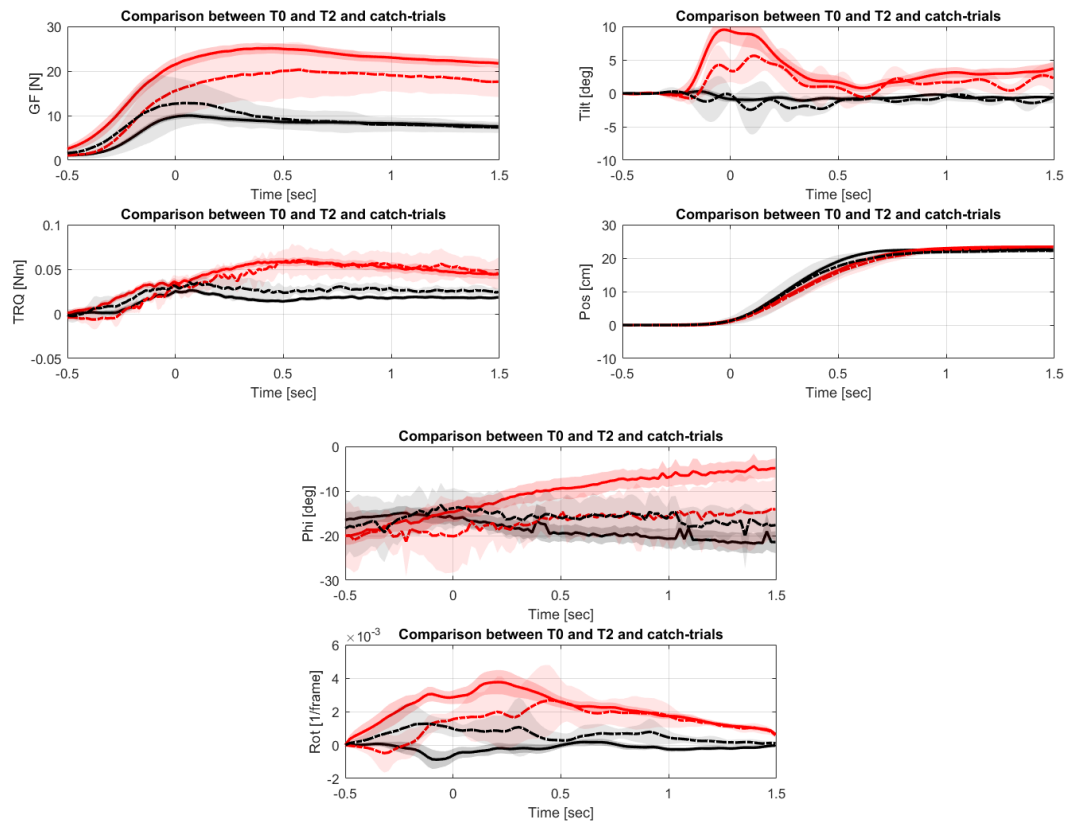


Figure A.17: Average evolution of the main variables for subject 9. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

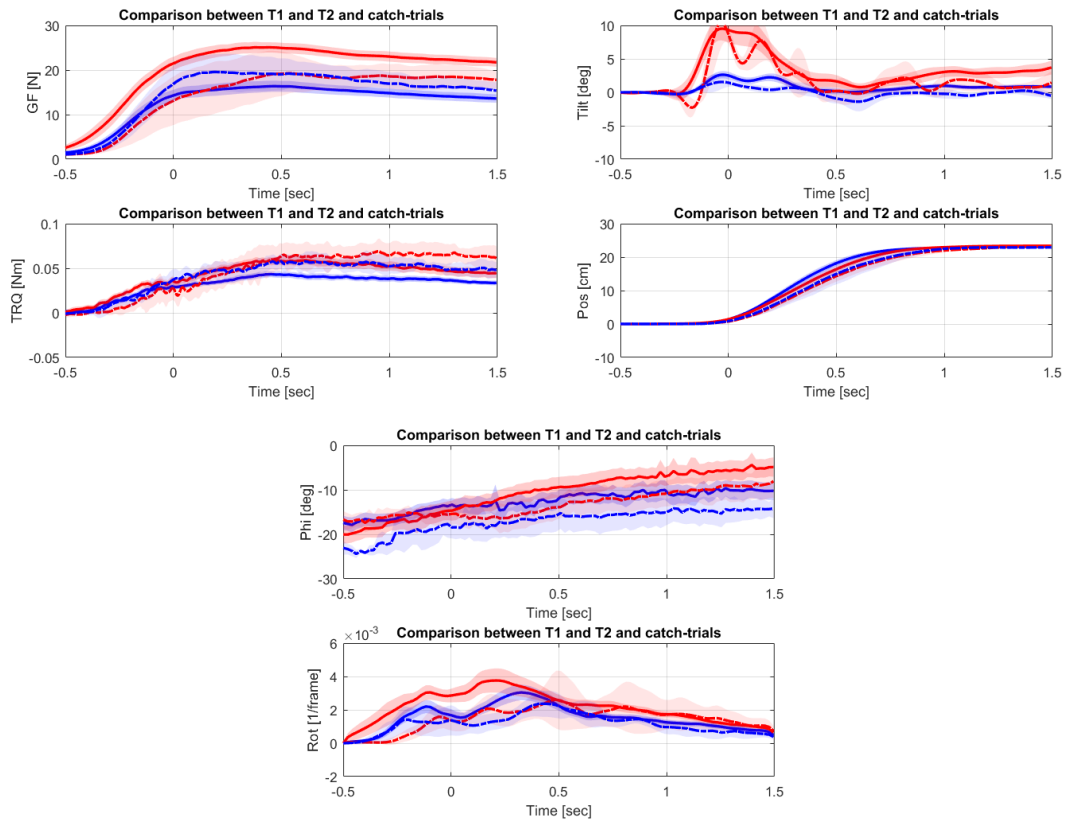


Figure A.18: Average evolution of the main variables for subject 9. We compare two levels of torques : T1 in blue and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

# Subject 10

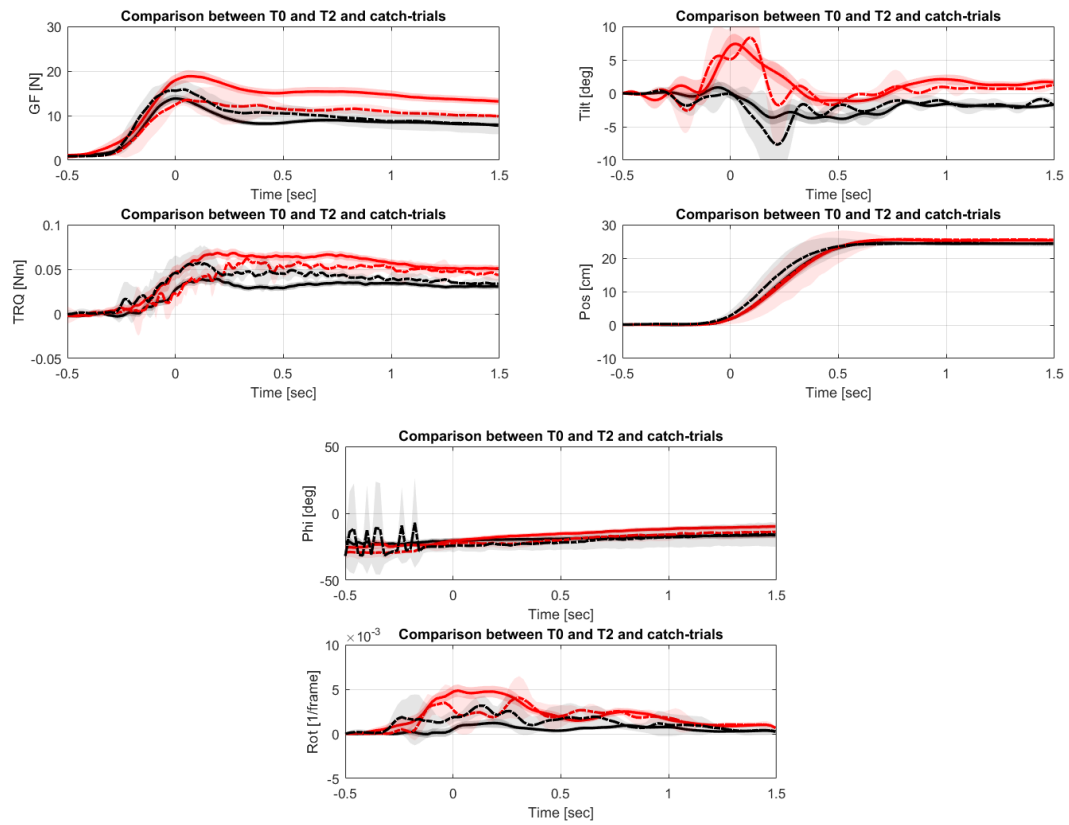


Figure A.19: Average evolution of the main variables for subject 10. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

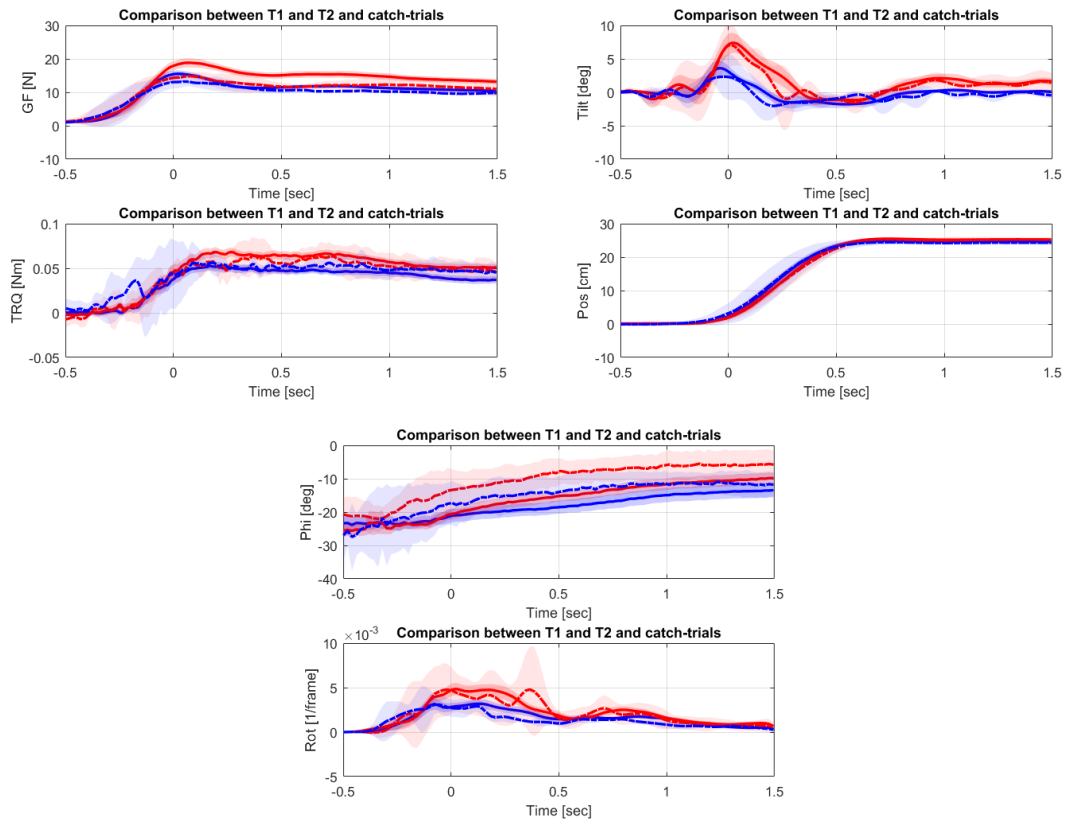


Figure A.20: Average evolution of the main variables for subject 10. We compare two levels of torques : T1 in blue and T2 in red. Doted lines represent the catch-trials mean for the torque condition of associated color.

# Subject 11

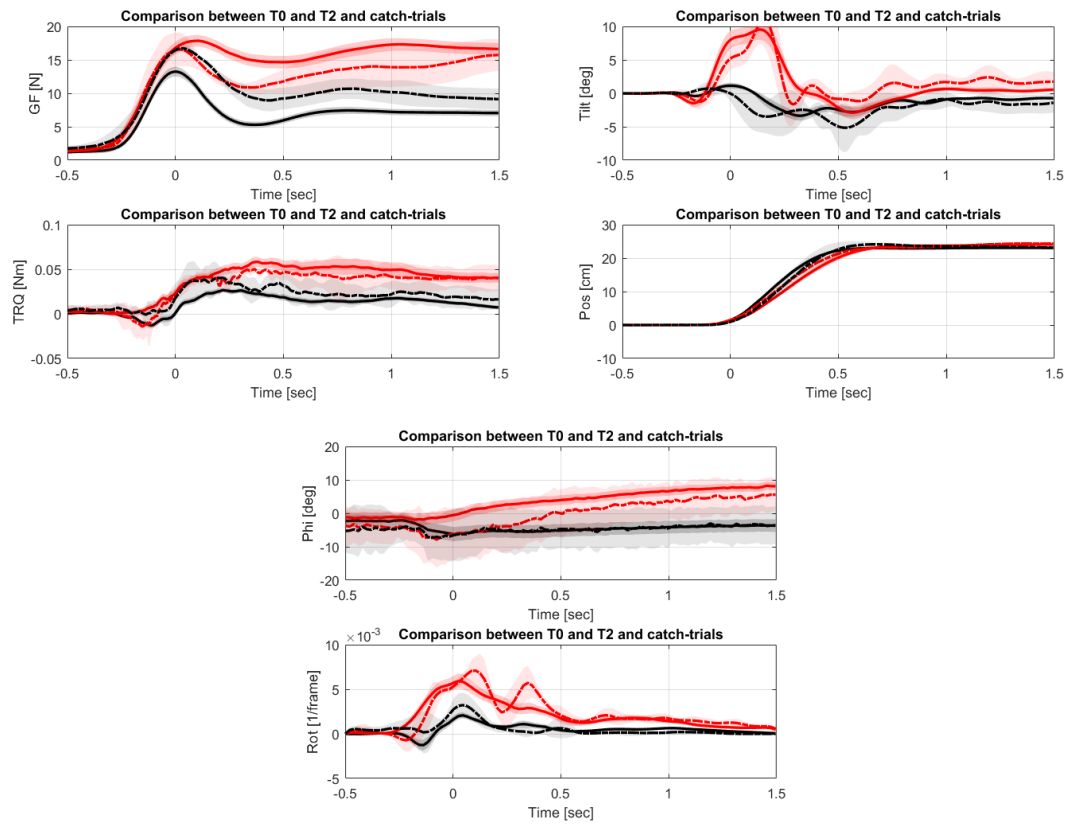


Figure A.21: Average evolution of the main variables for subject 11. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

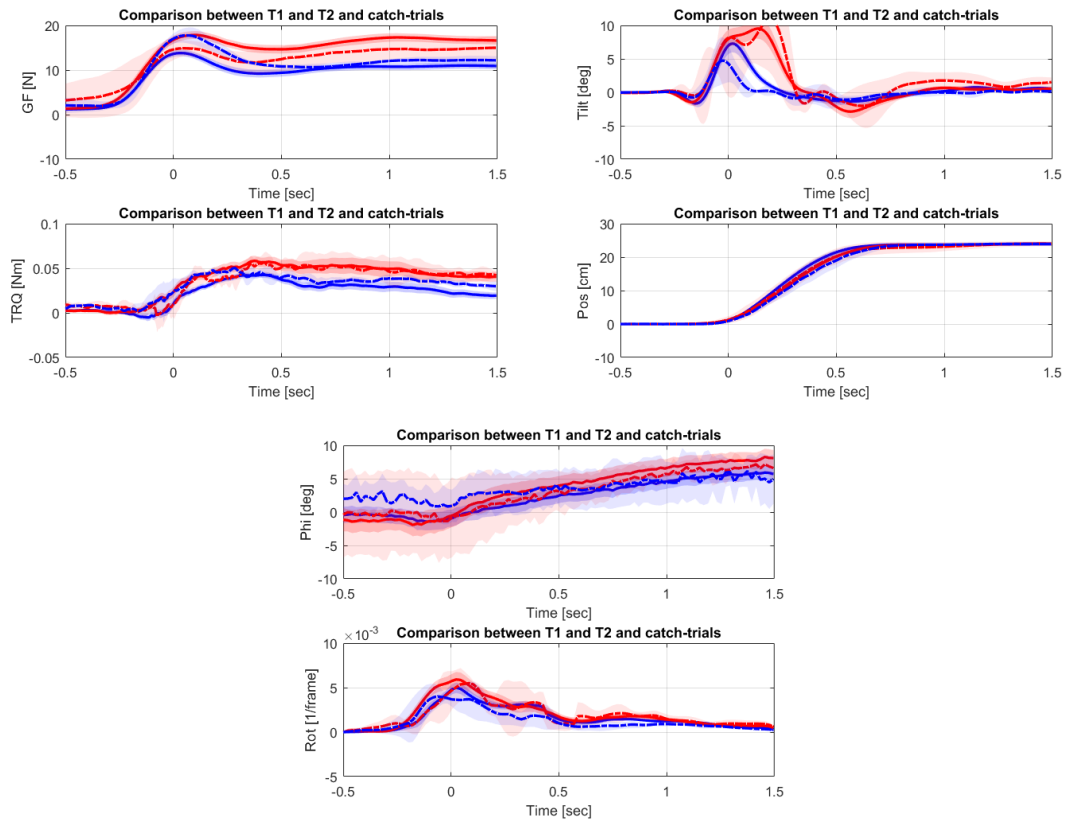


Figure A.22: Average evolution of the main variables for subject 11. We compare two levels of torques : T1 in blue and T2 in red. Doted lines represent the catch-trials mean for the torque condition of associated color.

## Subject 12

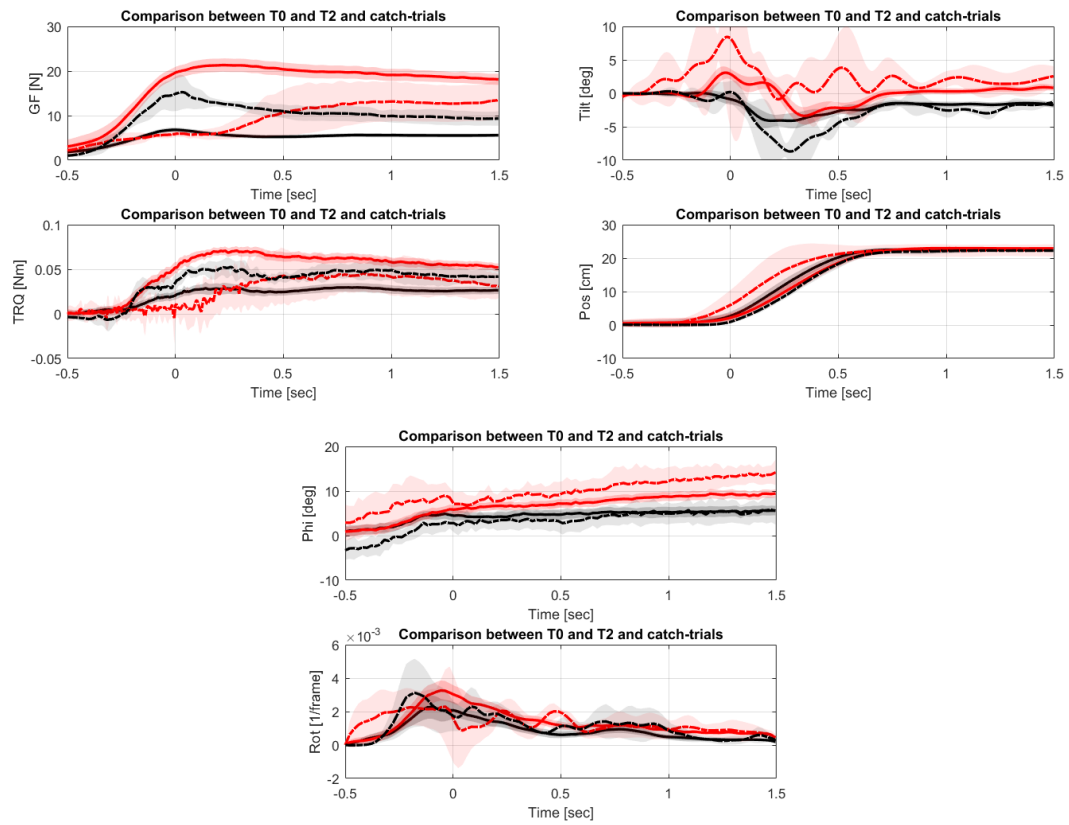


Figure A.23: Average evolution of the main variables for subject 12. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

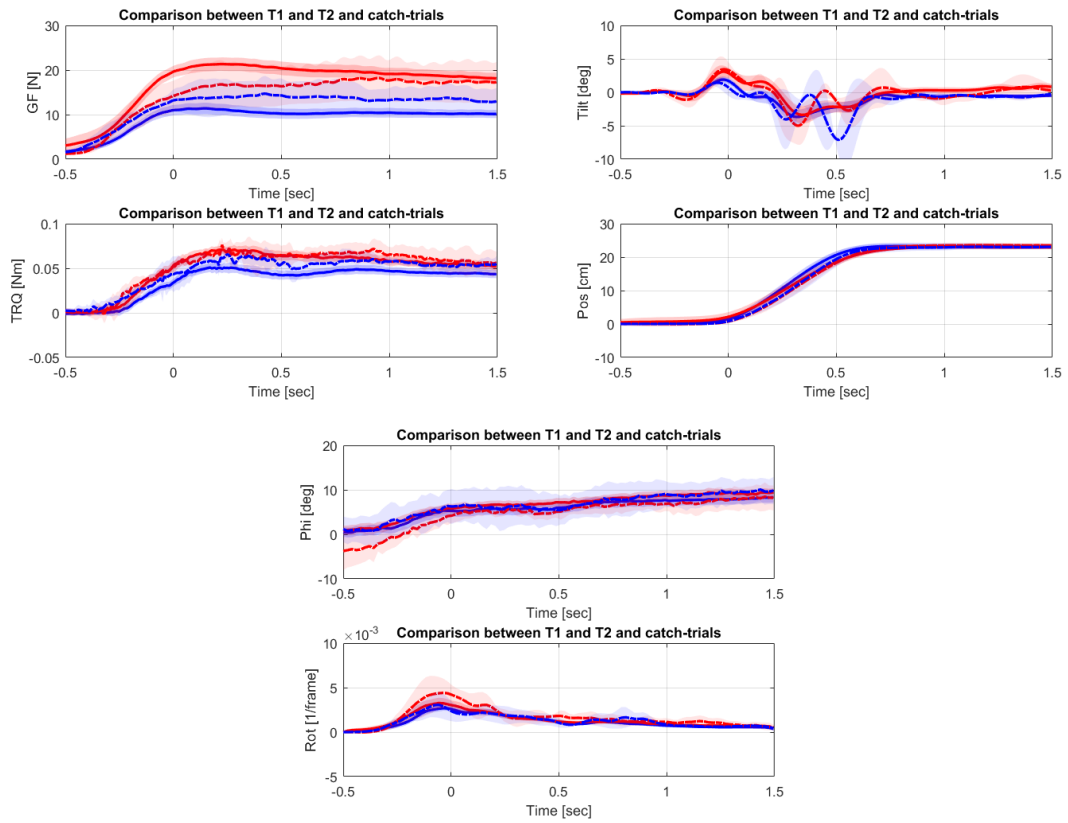


Figure A.24: Average evolution of the main variables for subject 12. We compare two levels of torques : T1 in blue and T2 in red. Doted lines represent the catch-trials mean for the torque condition of associated color.

## Average

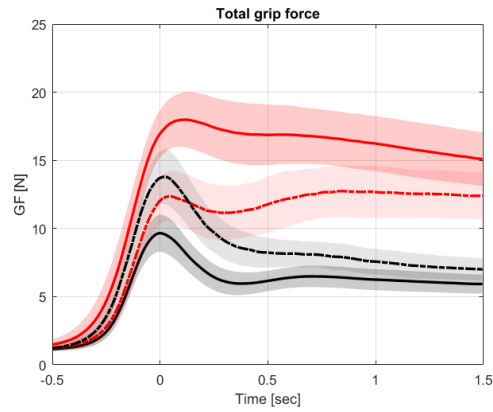


Figure A.25: Average evolution of the grip force. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

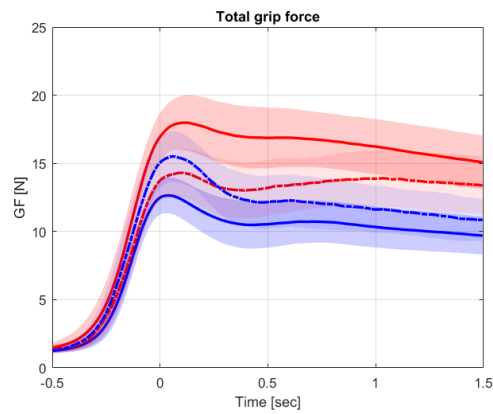


Figure A.26: Average evolution of the grip force. We compare two levels of torques : T1 in blue and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

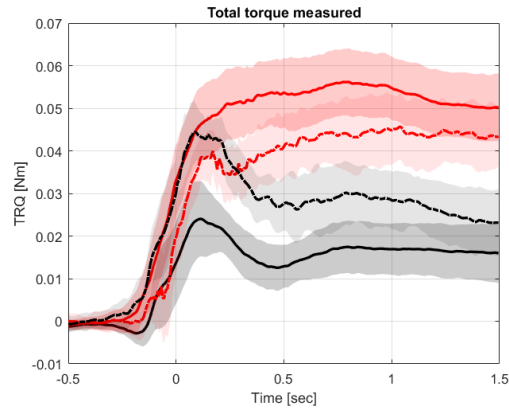


Figure A.27: Average evolution of the torque. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

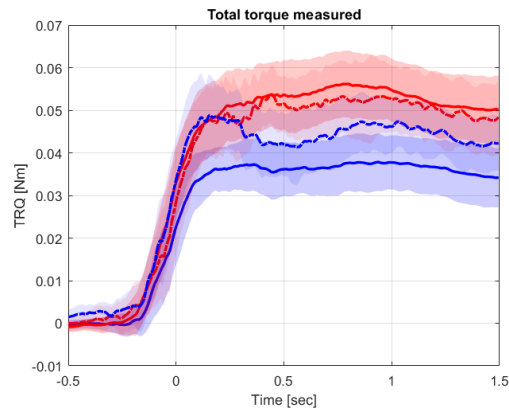


Figure A.28: Average evolution of the torque. We compare two levels of torques : T1 in blue and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

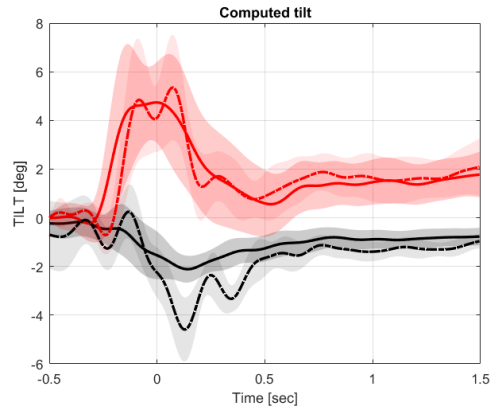


Figure A.29: Average evolution of the tilt angle. We compare two levels of torques : T0 in black and T2 in red. Doted lines represent the catch-trials mean for the torque condition of associated color.

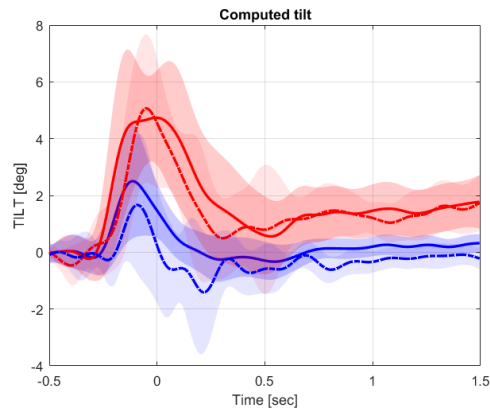


Figure A.30: Average evolution of the tilt angle. We compare two levels of torques : T1 in blue and T2 in red. Doted lines represent the catch-trials mean for the torque condition of associated color.

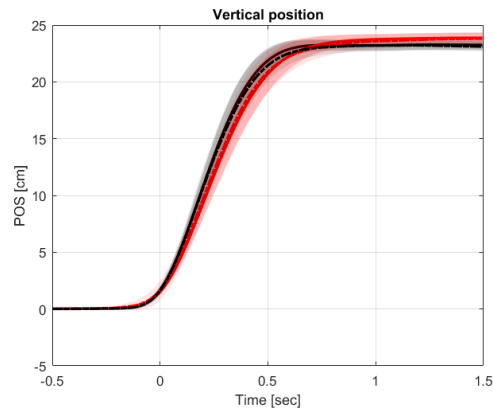


Figure A.31: Average evolution of the vertical position. We compare two levels of torques : T0 in black and T2 in red. Doted lines represent the catch-trials mean for the torque condition of associated color.

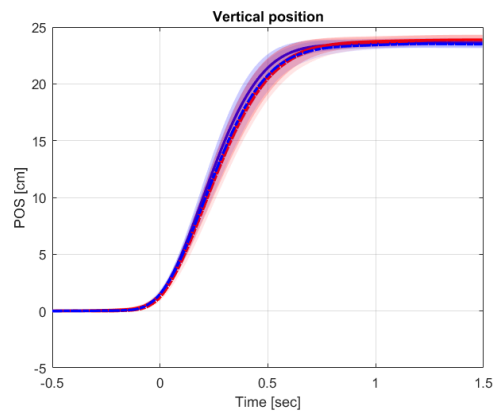


Figure A.32: Average evolution of the vertical position. We compare two levels of torques : T1 in blue and T2 in red. Doted lines represent the catch-trials mean for the torque condition of associated color.

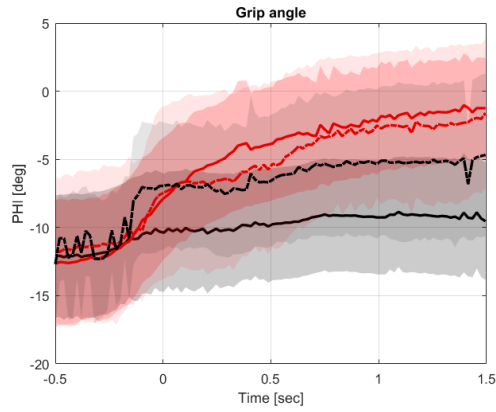


Figure A.33: Average evolution of the grip angle. We compare two levels of torques : T0 in black and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

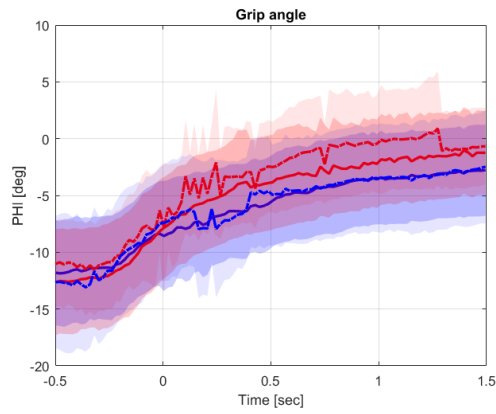


Figure A.34: Average evolution of the grip angle. We compare two levels of torques : T1 in blue and T2 in red. Dotted lines represent the catch-trials mean for the torque condition of associated color.

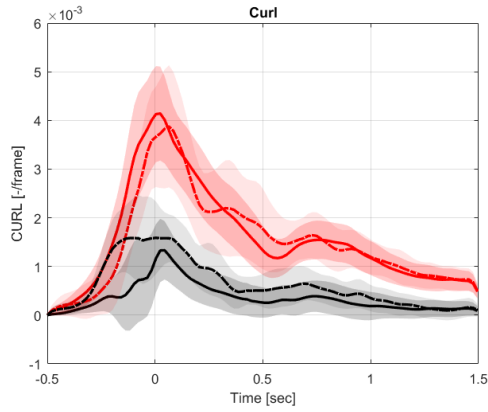


Figure A.35: Average evolution of the total index curl. We compare two levels of torques : T0 in black and T2 in red. Doted lines represent the catch-trials mean for the torque condition of associated color.

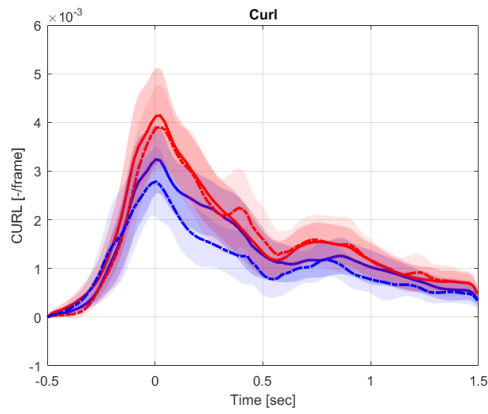


Figure A.36: Average evolution of the total index curl. We compare two levels of torques : T1 in blue and T2 in red. Doted lines represent the catch-trials mean for the torque condition of associated color.

# Appendix B

## Camera

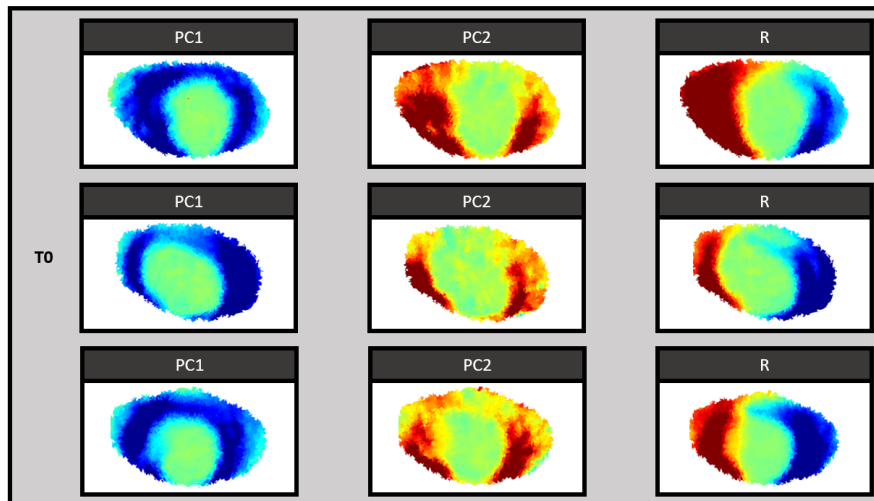


Figure B.1: Principle components of the strains (PC1 and PC2) and curl (R) of the fingerpad. Some adapted trials with T0 condition. The images are taken at the maximum total strain. Results are shown with a color scale, from dark blue for a high expansion to dark red for a high contraction.

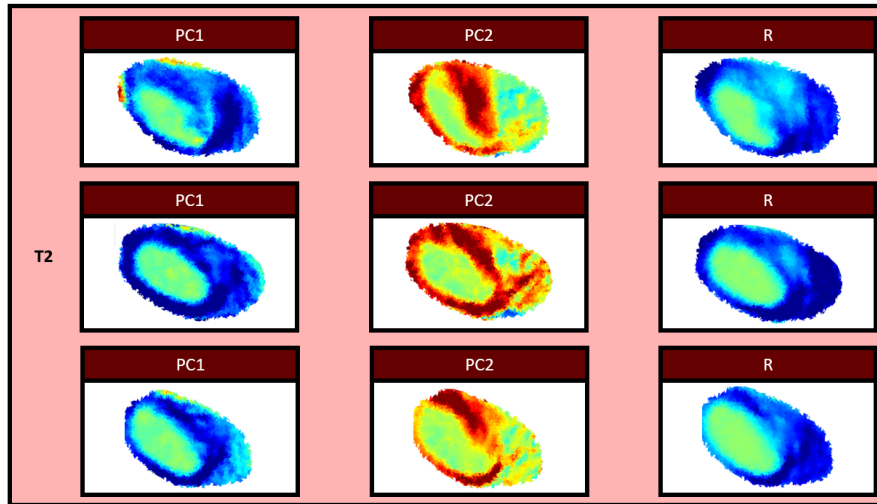


Figure B.2: Principle components of the strains (PC1 and PC2) and curl (R) of the fingerpad. Some adapted trials with T2 condition. The images are taken at the maximum total strain. Results are shown with a color scale, from dark blue for a high expansion to dark red for a high contraction.

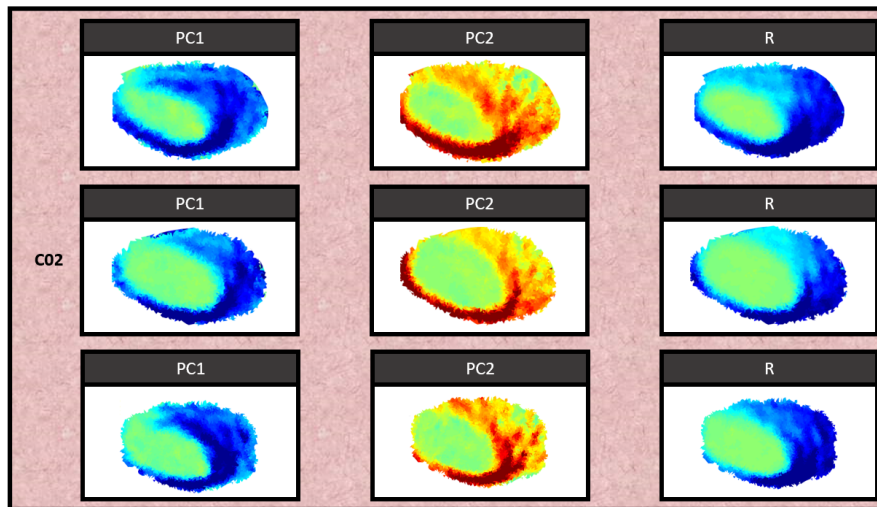


Figure B.3: Principle components of the strains (PC1 and PC2) and curl (R) of the fingerpad. Some catch trials with T2 condition. The images are taken at the maximum total strain. Results are shown with a color scale, from dark blue for a high expansion to dark red for a high contraction.

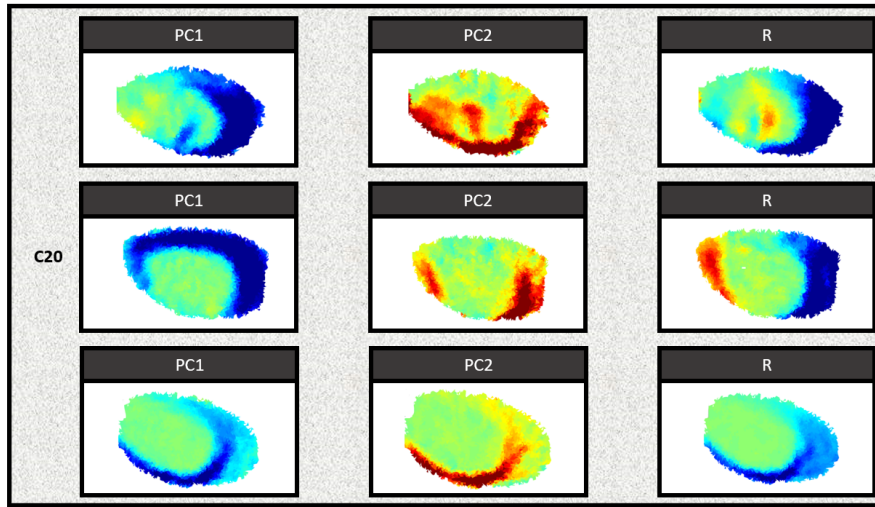


Figure B.4: Principle components of the strains (PC1 and PC2) and curl (R) of the fingerpad. Some catch trials with T0 condition. The images are taken at the maximum total strain. Results are shown with a color scale, from dark blue for a high expansion to dark red for a high contraction.

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