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Effect of gravity on object manipulation during controlled collisions

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1 Introduction

Manipulating an object, this is a task that may seem so trivial. But it is actually not that easy for everyone. The dexterity with which we manipulate objects is crucial in everyday life. And it is even more accentuated for people having health issues or having to cope with an unusual environment. A patient with Parkinson's disease or brain damage or even an astronaut might encounter difficulties performing these movements. This is the reason why it is noteworthy to study more deeply the strategies our brain establishes during object manipulation, and more precisely, the impact of gravity on it.

Among the plethora of tasks humans perform on a daily basis, collisions are not yet extensively studied in the literature. And it is even less investigated in unlikely environments. Our research topic is thus the effect of gravity on object manipulation during controlled collisions. This work aims to contribute to our knowledge expansion about mechanisms underlying grip control involved during collisions. Understanding how our brain works is an outstanding challenge and makes an important contribution to the brain-diseases field, to improve rehabilitation techniques after a stroke for instance.

1.1 Forces are involved in object manipulation

Humans in their everyday lives perform tasks involving complex interactions with objects in specific and varied environments. They take objects in their hands, move them and put them down afterwards without dropping them as, for example, when they pick up a glass of wine or a piece of chocolate. During all these actions, forces are applied by the hand and more precisely by the precision grip of the fingers. Indeed, when humans grasp an object with their thumb and their index finger, several forces are involved. A well adjusted coordination between a tangential force called the load force (LF) and a normal force called the grip force (GF) is crucial. Those two forces applied by the precision grip on the object's contact surface are illustrated in Figure 1 [1, 3, 11, 17].

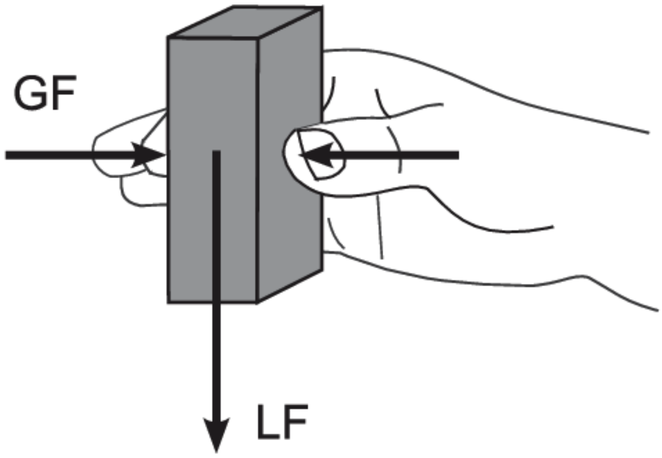

Figure 1: Grip force (GF) and load force (LF) applied by the precision grip (thumb and index finger) on an object [5]

The load force has an inertial and a gravitational component [17]:

$$\overrightarrow{LF} = m \cdot (\overrightarrow{a} - \overrightarrow{g}) \tag{1}$$

In Equation (1), m represents the object mass, $\overrightarrow{a}$ the object acceleration and $\overrightarrow{g}$ the gravity.

Grip force is linked to load force and must satisfy the following inequality to avoid slippage:

$$||\overrightarrow{LF}|| \leq \mu_s \cdot ||\overrightarrow{GF}|| \tag{2}$$

where μ_s represents the static friction coefficient at the finger/object interface.

1.2 Profiles and prediction of load and grip forces

Anyone who has played tennis has experienced the physical shock when the ball hits the racket. This sensation of unexpected weight shift happens likewise in the student's day in, day out being pushed when carrying heavy textbooks. These actions generate a sudden load change that is not always predictable. In the case of sudden and unpredictable load changes, sensory feedback relies on a very short lapse of time, preventing reactive actions to take place. Hence, prediction plays an important role even when it gives incorrect information, since it does not anticipate the unpredictable event. For instance, imagine you are playing golf. If your teammate suddenly plays a trick on you and replaces the golf ball by a ping-pong ball, your actions will be based on the prediction of hitting a ball that is heavier than it actually is. Thereby, your prediction about the ball weight will be wrong because you are used to playing with regular balls. These examples of unpredictable events demonstrate clearly the importance of the predictive function that always precedes and determines motor behavior. This component is important to maintain an adequate stability in predictable situations. The movement prediction and also the reactive update of this latter allow an accurate coupling between the load force and the grip force [3, 18].

Johansonn and Westling (1988) have shown that when an impact is expected when holding an object, preparatory actions are performed and grip force is thus increased before the impact to prevent the object from slipping. However, when the collision is not expected, it happens that the object is dropped by subjects [10].

Several studies analyzing the collision of an object with a target have demonstrated that before a predictable collision, during the transport phase, the object is accelerated and the load force varies gently in consequence. As a matter of fact, the inertial component of the load force changes due to the object's acceleration. Consequently, grip force evolves in parallel with the anticipated load force to keep an appropriate object stabilization. In order to anticipate the impact, grip force increases before the shock. At collision time, load force changes significantly. The coupling between grip force and load force is disrupted at this time [3, 10, 17, 18]. This can be observed on a typical graph representing the evolution of these forces during a collision towards the feet, as shown in Figure 2.

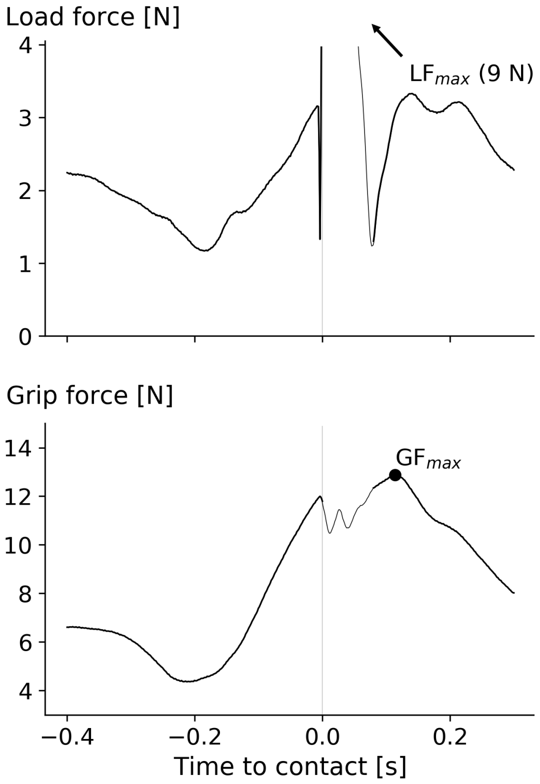

Figure 2: Typical load and grip forces profiles for one feetward collision in right-side-up posture. LF$_{max}$ and GF$_{max}$ are the maximum of load and grip forces respectively. Note the different scales of the y axis. The impact occurs at 0 second.

Surprising as it may seem, maximum grip force is always reached after the actual or anticipated time of impact. Therefore, the grip force maximum arises after the collision as seen in Figure 2. To demonstrate the predictive nature of the late grip force component, Bleyenheuft and colleagues (2009) have shown that when a collision is expected but does not occur, there is still a grip force increase after the time at which impact should have occurred. In their study, subjects first performed five impact trials, where the load of a hand-held object was quickly increased by dropping a mass attached to the object. At the sixth trial, subjects were not aware that the impact would not occur. However, the grip force maximum still occurred at the same time as in the five previous impact trials. Therefore, whether there is a collision or not, the maximum of the grip force is time-locked after the contact (or expected contact) time [3].

In their paper published in 2011, White and collaborators have demonstrated that this pre-programmed grip force peak was reached approximately 65 ms after contact. It might be confusing that grip force maximum occurred 65 ms after contact. On the one hand, the risk to drop the object is maximum at collision time, when load force is greatest. On the other hand, increasing grip force augments stiffness at hand/object interface, which induces a reduction of the damping properties. Consequently, the 65 ms latency allows a trade-off between an efficient damping and a secure object stability [18].

The fact that adaptation of grip force is anticipatory illustrates that motor control relies on predictions. The predictive mechanism also integrates a reactive component, which is of lesser importance [3, 18].

1.3 Gravity perception relies on a multisensory cue combination

Humans' interactions with objects are constrained by gravity. Moreover, humans' perceptions of their environment innately factor in their experiential knowledge of the force of gravity. But it is not always straightforward for humans to estimate their orientation because they do not have a specific organ doing that. Gravity estimation, which is the assessment of the gravitational vector, relies on a multisensory integration of information. Vestibular, visual and somatosensory information are combined together with different weights. Since single signals about gravity are noisy and ambiguous, multisensory cue combination allows humans to perceive the environment in an unified way and to anticipate gravity effects with greater validity. Note that when subjects have a neurological disease, it can affect their gravity perception, and the influence of each sensory signal will not be weighted in the same way as they would by healthy subjects. In addition to multisensory signals, humans have priors based on their knowledge of the world. These priors are established by an internal model. They can improve the accuracy of gravity perception, unless if they are employed in unlikely environment [7, 12, 13, 19].

Firstly, the vestibular system plays a major role in gravity perception. The inner ear contains vestibular receptors. There are three semicircular canals and two otolith organs per ear. The first ones detect angular acceleration, they are thus sensitive to head rotation, while the second ones perceive linear acceleration. Otolith signals give inertial and gravitational information. These two components cannot be distinguished if only based on otolith signals. For example, a backward head tilt is perceived in the same way as a forward acceleration. Thus, cues must be disambiguated in order to discriminate inertial and gravitational forces [7, 12, 19].

Secondly, vision gathers both static and dynamic signals to assemble cues about gravity. Nevertheless, visual system does not take gravity directly into account. Indeed, it considers the acceleration of retinal projected images. Lacquaniti and colleagues reported in 2014 that visual and vestibular system interact together. Indeed, if participants have to estimate the acceleration time of a target, they will achieve the best results when they are right-side-up and when there is a right-side-up visual scene. Their estimation will be the worst when subjects are right-side-up while the scene, without visual cues, is tilted by 45^o [12]. As humans age, the weight of visual cues in the multisensory signal becomes more important because their vestibular system is less reliable [7].

Thirdly, the somatosensory system gathers all the sensory information related to the body thanks to mechanoreceptors. In their paper from 2016, Bringoux and colleagues reported that somatosensory signals are essential for body orientation perception. Indeed, they showed that a patient with somatosensory loss failed to perceive his body orientation even if the visual and vestibular systems were intact. Strikingly, the patient did not take into account available visual signals at all for this task [4].

Depending on the specific environment, human perception of gravity will differ. Each of the sensory sources discussed above will play a greater or lesser role and with varied reliability depending upon the specific situation. For instance, when a subject is lying down, the relevance of vestibular information decreases [7, 13, 19].

Human sensory systems encode information with respect to egocentric frames, so frames that are body-centered. Each sensory system has its own egocentric frame. However, environment is perceived in an allocentric frame, which is aligned with gravity, so which is Earth-centered. This reference frame transformation, although not complete, allows a stable representation of the surrounding environment, since it is not influenced by the human movements. This incomplete transformation gives rise to an intermediate reference frame [7, 19].

1.4 Gravity impacts object manipulation

Interestingly, humans do not manipulate objects in the same way if they have to move them towards the head or the feet and thus, grip force behavior is not exactly the same in case of headward or feetward movements. The movement kinematics are different depending on its direction. As a matter of fact, Le Seac'h et al. (2007) made a study about pointing movements. They demonstrated that in the right-side-up orientation, feetward movements had a greater relative time-to-peak-velocity than headward movements. More specifically, they showed that it took more time to decelerate an object than to accelerate it in headward movements, whereas it took the same time for feetward movements. When subjects were horizontally reclined with their eyes open, these asymmetries were not observed for movements from feet to head or from head to feet, so these variations were due to gravity. But when participants were reclined with eyes closed, these differences were again observed, showing that, in addition to gravity, the body axis also played a role (smaller than the gravity effect). Thereby, reference frame could change with vision [13]. This could lead to the assumption that when eyes are open, the reference frame is allocentric whereas when they are closed, it becomes egocentric.

Concerning collisions, White and collaborators (2011, 2012) also observed asymmetries between headward and feetward movements in the right-side-up orientation. For headward movements, the inertial component made a positive contribution to load force while in feetward movements, this component contributed negatively to load force. This is the reason why load force was bigger at the time of headward collisions. Hence, grip force was greater in this case compared with feetward collisions [17, 18].

In order to study effects of gravity, White et al. (2012) also considered microgravity. The particularity of microgravity is that the gravitational component in the load force vanishes. Consequently, this force is only proportional to acceleration and is thus equal to zero at rest. That is why there is the same probability to observe slips in both direction when gravity is zero. During the transport phase in microgravity, grip force is coupled to load force as in normal gravity condition. Because of the symmetry of acceleration profiles in opposite movements, maximum load force values are similar. Hence, as outlined in Figure 3, grip force values were also similar. Quite remarkably, White and colleagues also observed that at contact, i.e. 8 ms before peak load force, grip force had proportional maximum values whichever the gravity. Indeed, as shown in Figure 3, grip force maximum for headward movements was always on average higher than for feetward collisions. This could show that subjects adopt the same grip force predictive component as in normal gravity despite the fact that there is no more gravitational bias. However, it took more time to reach its maximum in headward movements versus feetward movements. This difference between headward and feetward collisions remained even after a very long exposure to microgravity [17].

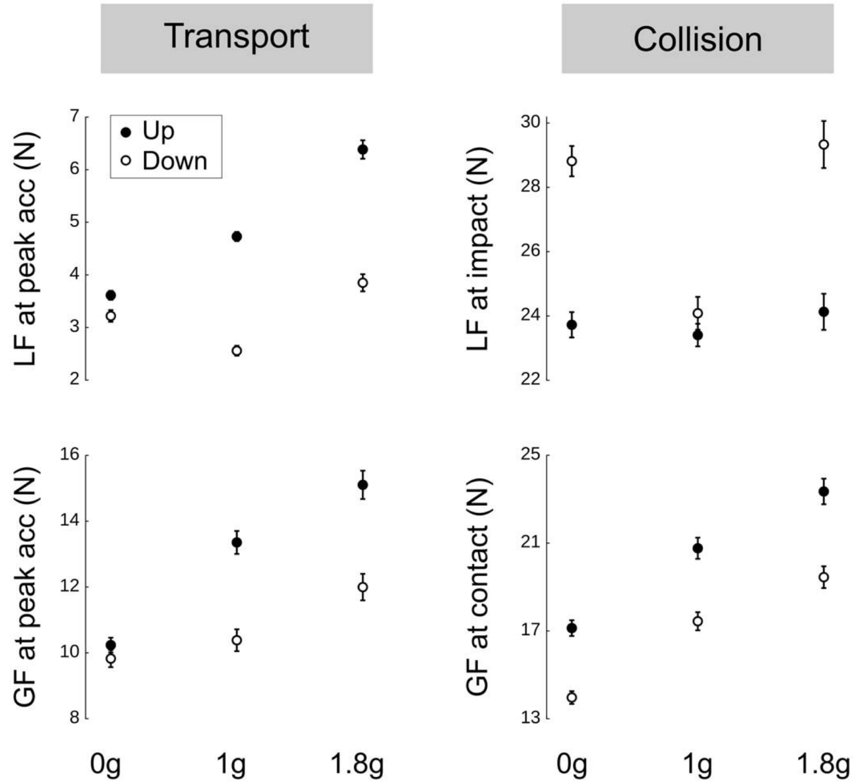

Figure 3: Load and grip forces during transport and collision phases for three gravity conditions (0g, 1g and 1.8g). Note the different scales of the y axis. Up: headward collision; Down: feetward collision. [17]

1.5 Movements are based on an internal model

Because humans have been subjected to gravity since birth, the brain has an internal model representing gravity. This model predicts gravity effects and thus allows humans to compensate for them and adjust behaviors. This process can be described in two different models illustrated in Figure 4: the inverse and the forward model. Let us take the example of a reaching movement of a hand holding an object. The inverse model estimates the arm motor command based on the desired trajectory. The output of this model is sent to the arm and to the forward model. Indeed, this latter model receives an efference copy of the motor command based on which it will predict the next arm trajectory. This output allows the grip force controller to calculate the minimum grip force that is sent to the hand muscles. The internal model is thus substantial for movement prediction [11, 14].

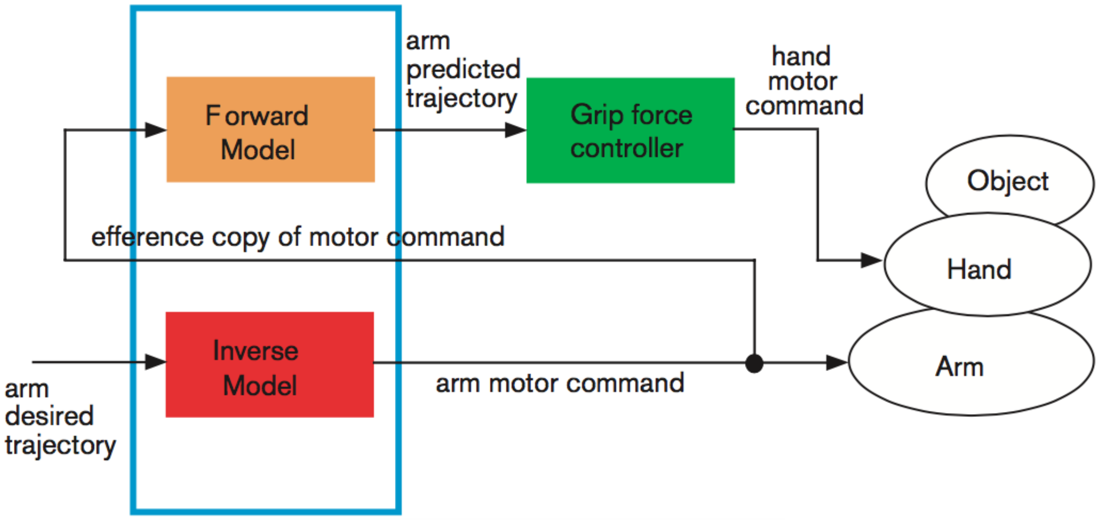

Figure 4: Internal model schema including inverse model, forward model and grip force controller used in arm reaching, arm trajectory anticipation and grip control respectively [11]

The brain takes advantage of gravity to optimize muscular efforts. As a matter of fact, gravity exerts a resistive force to accelerate an object headward while enabling it to accelerate more easily feetward. When participants are in microgravity, the difference between headward and feetward movements changes slightly supporting the theory that the internal model adapts itself to new environments and re-optimizes movement planning. Indeed, this model not only takes into account the environment, but also finger and object properties as their coefficients of friction. The internal model is therefore crucial to plan the grip force that must be exerted [8].

In a nutshell, the brain is able to synchronize load force and grip force and to program movement kinematics based on an internal representation of gravity.

1.6 Research questions and hypotheses

This leads us to some research questions about collisions, which are movements that have not yet been investigated much. First of all, one can ask if when being upside-down, the grip force is greater for headward collisions, as White et al. (2011, 2012) have shown to be the case in right-side-up condition, reflecting an egocentric reference frame or whether it is larger for feetward collisions, consistent with an allocentric reference frame [17, 18]. Another interesting question is to know how the grip force profile is influenced by the subject position, such as supine or upside-down. Additionally, the effect of vision can be studied to know if there is a difference between grip force whether collisions are performed with eyes open or closed.

To attempt to answer to those questions, it would be interesting to know whether the programming of grip force and movement kinematics operates in an allocentric (Earth-centered) or egocentric (body-centered) reference frame. That is to say, whether grip force and movement control take into account gravity direction or body orientation.

In the right-side-up posture, load force is theoretically greater for headward collisions since it is impacted by gravity. Indeed, for headward movements, the inertial component makes a positive contribution to load force while in feetward movements, this component contributes negatively to load force. This is the reason why load force is bigger at the time of headward collisions. In the supine orientation, gravity makes the same contribution whether the collision is toward the head or the feet, so the load force should be equal in both directions. And in the upside-down posture, subjects are in the opposite position compared to the right-side-up posture. The inertial component contributes positively to load force during feetward collisions, explaining why load force should be greater for feetward than headward collisions.

On the one hand, if the reference frame is allocentric, we expect grip force to be also greater for headward movements when being right-side-up, as the load force. In the supine posture, grip force should be the same whichever the collision direction, following the load force pattern. Regarding the upside-down position, grip force should be greater for feetward than headward collisions if the reference frame is Earth-centered.

On the other hand, if the reference frame is egocentric, because we are subjected to gravity since our birth and that we are used to being in a right-side-up posture, it is our reference position. Whichever the position, the same behavior would be adopted. Grip force should thus be greater for headward collisions in all orientations if the reference frame is body-centered.

Our assumption is that in the right-side-up posture, we will get the same results as those described in section 1.4, so that grip force will be greater for headward than feetward collisions. In addition, we expect that the reference frame remains allocentric when subjects are supine and upside-down. But if subjects close their eyes in the supine posture, the study of Le Seac'h and collaborators (2007) leads us to believe that since they will no longer have visual information, participants will accord less influence to their gravity perception and we expect that the reference frame will tend to become egocentric. We also assume that participants will not have the ability to adapt completely to a new environment after being exposed to it during a short time. We expect them to accord less influence to their gravity perception and base their behavior on movements they are used to.

2 Protocol

2.1 Experiment specific goals

Prior studies have established that humans use a larger grip force for headward than feetward movements even if they are in microgravity where slip chances are equal for headward and feetward movements [17]. Building on these facts, the focus of our research will be on a deeper analysis of these differences in various conditions.

2.1.1 Primary objectives

We conducted some experiments in order to assess how humans adapt their grip force during collisions with an object in altered gravity.

The precise goals are the following:

- Study of grip force profile during collisions when in an upside-down position.
- Study of grip force profile during collisions when being tilted at 90^o.
- Study of grip force profile during collisions performed with eyes open and closed.

2.1.2 Additional goals

The study of the kinematics behavior during collisions is also a noteworthy point.

Furthermore, it is believed that when humans manipulate an object in normal gravity, they naturally place the centers-of-pressure of their precision grip in such a way as to hold an object in a vertical position. However, when in an upside-down position, Opsomer et al. (2021) had observed that these centers-of-pressure tended to be misaligned [15]. Indeed, in this condition, gravity acts as if the object is pushed towards the head, which is not common.

This leads us to three additional purposes:

- Study of the kinematics involved during collisions in different conditions.
- Study of the evolution of fingers' centers-of-pressure during collisions when in an upside-down position.
- Study of the evolution of fingers' centers-of-pressure during collisions when being tilted at 90^o.

2.1.3 Research questions

As a reminder, our research questions are the following:

- Is grip force greater for headward or for feetward collisions when in an upside-down position?
- Does grip force profile change when being in a different position such as supine or upside-down?
- Is there a difference between grip force whether the eyes are open or closed?

2.2 Materials and methods

2.2.1 Participants

Eighteen volunteers aged from 21 to 32 years (eight women and ten men) participated in this study. The participants reported being right-handed and used their right hand to perform the assigned tasks. None of them reported having any motor or heart disabilities. They all had normal or corrected-to-normal vision. Participants provided written consent to participate in the experiments after being made aware of potential experimental risks.

The procedures were approved by the ethics committee of the Université catholique de Louvain. All participants were naive to the purpose of the experiments and a debriefing was conducted after the experimental session to get their general feelings about the task.

2.2.2 Experimental setup

Participant was asked to hold a grip-lift manipulandum (GLM) between the thumb and index finger of his right hand. The manipulandum (Arsalis, Belgium), illustrated in Figure 5, weighed 260 grams, had a height of 9.1 cm, a width (so a grip aperture) of 3.75 cm and a depth of 4.8 cm. The tridimensional force and torque sensors (Mini 40 F/T transducers) ensured a uniform measurement of the different forces and torques applied by the subject. The vertical acceleration was detected with a one-dimensional accelerometer. The four CODA micro markers of the manipulandum were detected by CODA cameras (Codamotion CX-1 units, Charnwood Dynamics), registering its position and orientation in space. The GLM also measured skin moisture of the fingers thanks to a circle printed circuit board present in the center of the two faces that the subject held with his precision grip [16].

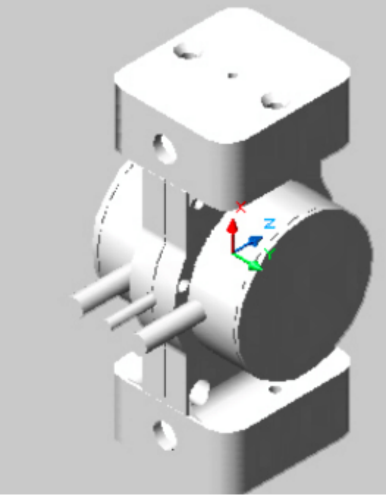

Figure 5: Grip-lift manipulandum used during the experiments [16]

A rotating custom-made structure was used in order to carry out the experiments. It was consisted of a chair, two identical targets and a metallic frame. This set-up can be seen in Figure 6.

In our experiments, the subject was seated in a chair the entire time with his back up against the backrest. A six-point harness secured him in the chair as this latter was manipulated in different positions, so that the participant's position in the chair stayed globally the same along the whole task. His feet were held in place with foot straps. He was placed in front of two targets that were collided by the held object. The targets were located 21 cm above and below the subject's shoulder. The two targets, highlighted by red lines in Figure 6, were thus spaced 42 cm apart, in front of the subject. Their position could be adapted along both the horizontal and vertical axes in order to ensure that the participant was comfortable with the tasks.

Figure 6: Subject performing collisions in the rotating chair in right-side-up posture with eyes closed. The two targets are represented by the red lines. The manipulandum is framed in red.

Audible sounds were present to guide the participant along the tasks. Every 1.5 seconds, a new instruction was given. The fast movements were dictated by these sounds indicating if the subject had to collide the manipulandum towards his head or his feet. The difference between the two types of instruction was achieved through frequency differentiation. The start of each task began with an audible sound at a frequency of 500 Hz, head-instructions had a frequency of 2000 Hz while feet-instructions had a frequency of 500 Hz.

The metallic frame surrounding the chair allowed the chair to be tilted at different angles. Three positions were trialed in this research in a pseudorandom order by each subject. The position where the participant was in a right-side-up posture is the control position. Another orientation was when the chair was tilted at 90^o in the frontal plane with respect to the right-side-up posture. This supine body orientation is the closest from the microgravity condition. It is interesting to study this condition since the gravitational component does not influence the load force. Thus, this force only depends on acceleration. That is why the probability for observing slips is the same for headward and feetward movements. In the last position, the chair was rotated 180^o with respect to the control position, so the subject was upside-down. This condition could be interpreted as being a -1g environment.

2.2.3 Experimental trials

Subjects washed their hands with hydro-alcoholic gel before the beginning of the experiments. In this way, their skin had its natural hydration level.

In a block of collisions, the subject moved the manipulandum headward or feetward to collide one of the two targets. If the sound was high-pitched (low-pitched), the participant had to collide in the direction of his head (feet). After each collision, the subject replaced the manipulandum between the two targets. No particular instructions were given about the grip force and the velocity. One block was composed of twenty collisions: ten headward and ten feetward collisions.

The participant performed several blocks, guided by the instructor about which time he was supposed to open and close his eyes during the experiments. The instructor verified by careful observation that the subjects followed the instructions accordingly. Of note, no blindfold was used for the eyes closed tasks.

The following procedure was applied for each participant.

1. The subject took his seat in the chair in right-side-up position.
2. A coefficient of friction test was performed under three conditions: one where the subject rubbed the manipulandum slightly, one where he applied more force on it and another where he rubbed it harder.
3. The participant completed two training blocks with eyes open and two training blocks with eyes closed in the right-side-up posture to get used to the task.
4. Three positions were tested in a pseudorandom order to perform the collisions: the right-side-up, supine and upside-down orientations. In each of them:
    - A coefficient of friction test was performed.
    - Eight blocks of twenty trials were conducted, four with eyes open and four with eyes closed. The subject alternated between eyes open and closed, starting with eyes open. In one block, headward and feetward trials were performed in random order. A break was taken between each block.
    - A coefficient of friction test was again performed.

More precisely, the coefficient of friction test is a method from Barrea et al. (2016) that enables the estimation of the static coefficient of friction of precision grip [2]. It is a calibration task where the subject has to hold the manipulandum in the same way as during collisions and has to perform vertical back-and-forth movements. It takes into account the fact that this static coefficient of friction does not evolve linearly with the normal force. The coefficient of friction is computed as: $\mu_{static} = k * NF^{n-1}$, with k and n parameters and NF the normal force exerted on the manipulandum.

2.2.4 Duration of experiments

Because in each of the three positions, the participant did four blocks of twenty collisions with eyes open and four blocks of twenty collisions with eyes closed, he performed 480 collisions in total.

Strapping the subject into the chair and providing instructions about the experiments took approximately 20 minutes.

Seven coefficient of friction tests were performed in total (one before the training and one before and after each position). Each test lasted 2 minutes, therefore 14 minutes were required for those tests.

One collision lasted 1.5 seconds. The participant had 5 seconds to take the manipulandum in his hand at the beginning of the task and 5 seconds at the end to put it down. He performed 20 collisions, therefore one block lasted 40 seconds. Between each block, the participant took a break. If he was right-side-up or supine, each break lasted 30 seconds. Nevertheless, when he was in the upside-down condition, the subject was straightened up and took a break during approximately 3 minutes. For training blocks, since one block of collisions lasted 40 seconds and that a 30-seconds break was taken between each block, the entire training lasted less than 5 minutes. In the right-side-up and supine conditions, since collisions and breaks lasted also 40 seconds and 30 seconds respectively, one entire condition (eyes open + closed) lasted approximately 10 minutes. For the upside-down orientation, collisions took the same time but the break plus the change of position was estimated to 3 minutes. That is why experiments for this condition lasted on average 30 minutes.

All in all, total experiment time for one subject was estimated at 1 hour and 30 minutes.

2.3 Parameters measured

1. The tangential and normal forces at finger/manipulandum interface.
2. The tangential and normal torques.
3. The manipulandum three-dimensional position.
4. The manipulandum acceleration.

2.4 Data processing

Data were analyzed using custom routines in Python 3.7.

As illustrated in Figure 5, the x direction was defined vertically while the z axis was in the horizontal direction, tangentially to the manipulandum sensors. The y direction, for its part, was normal to the sensors. This reference frame in which signals were recorded is egocentric. The x position increased towards the head and became negative towards the feet, whichever the participant's orientation. For the position signal, the 0 was defined as being located in between the two targets. Therefore, the headward target was always located at +21 cm whereas the feetward target was located at -21 cm on the x axis.

The position of the center of mass of the manipulandum was not directly measured but it was calculated from the 3D position of the four CODA micro markers using custom programs in Python. The velocity was computed as the derivative of the filtered vertical position. We focused more deeply on the vertical direction since it was the collisions' direction.

For each individual collision, movement onset was defined as the last time at which the velocity was lower than 10% of the peak velocity before contact. We defined that the movement ends 300 ms after impact.

The load force magnitude is the norm of the tangential load forces: $LF = \sqrt{(F_x)^2 + (F_z)^2}$ with F_x and F_z the vertical and horizontal components of the load force respectively. F_x is the sum of the forces applied in x direction on the left and right sensors. Similarly, F_z is the sum of the forces applied in z direction on the left and right sensors. The grip force is the mean of the absolute normal forces applied by the thumb on the left sensor and by the index finger on the right sensor.

The acquisition frequency of the forces, torques and acceleration signals was 800 Hz. The coefficient of friction data (measured during the coefficient of friction test) were low-pass filtered with a fourth-order Butterworth filter, having a cutoff frequency of 20 Hz. A 200 Hz acquisition frequency was used to record the position signal. This signal was also filtered with a Butterworth low-pass filter of order 4, but the cutoff frequency was set at 15 Hz.

All recorded force, torque and acceleration signals were refocused according to a baseline defined when the subject had not yet touched the manipulandum.

2.4.1 Technical issues

Unfortunately, some technical issues were encountered during CODA data acquisition. This was probably due to a false contact in the circuit board. Indeed, a switch between markers occurred in some cases, altering the corresponding positions. Several changes were made to the positions extracted from the CODA data to deal with these problems, otherwise position would not be representative of the actual position. But for three blocks on all blocks, the data were unusable. Firstly, there were missing data for one subject in his first block of the upside-down condition with eyes open. Data were set to NaN for this block. Secondly, for one participant in supine posture with eyes open and one participant in upside-down position with eyes closed, the third data block was also set to NaN since there were recording problems making the data unusable.

2.4.2 Rejected collisions

Some collisions had to be rejected since they did not correspond to proper desired movements. For instance, subjects sometimes stopped their trajectory en route to the target, then restarted directly and hit the target. This was not considered as a proper movement for our experiments. Collisions were rejected following three different criteria.

The first criterion was about the amplitude of the movement. If it was lower than 6 cm or higher than 26.9 cm, the manipulandum was considered to be too close or too far from the target to correspond to a proper collision. Hence, in this case, the associated collision was rejected.

A second reason to reject a collision was if the movement onset, so the time at which the velocity was 10% of the peak velocity, was less than 100 ms before the impact or more than 600 ms before the impact. Such a short or long interval did not seem to correspond reasonably to a transport phase in the configuration of the experiments.

The last rejection criterion concerned the acceleration. If the maximum of the acceleration absolute value was lower than 50 m/s^2, this acceleration was not considered high enough to correspond to a collision.

By applying these criteria, 3% of the collisions were rejected. Note that one third of these rejected trials were performed in the upside-down condition with eyes closed.

2.5 Statistical analyses

Throughout this report, result values are given as mean ± standard deviation unless otherwise specified.

Most of the following graphs synthesizing the twelve different experimental conditions (three postures, two collision directions and two vision conditions) represent mean with the associated standard error across subjects. For each subject in each condition, the mean of the variable of interest of the twenty collisions across the four blocks was computed. Then, the average of these values across the eighteen subjects and the associated standard error were calculated in the twelve experimental conditions.

Three-factors repeated measures ANOVA were conducted in order to assess the influence of posture (right-side-up, supine and upside-down), movement direction (headward vs feetward) and vision (eyes open vs closed) on the dynamic and kinematic variables of interest. Sometimes, these repeated measures ANOVA were performed to analyze the effect of block, movement direction and vision for each position.

Post hoc tests were then performed, including paired t-test comparing subject means between different conditions. When a significant main effect of posture was detected, or when a significant interaction between posture and another factor was detected, these post hoc analyses were performed with a Bonferroni correction that was applied in order to take into account multiple comparisons.

With the aim of determining the evolution across the four blocks, a linear least-squares regression was performed to determine if this evolution was statistically different from zero. To reduce inter-subject variability, for each subject, the average value of the four blocks was subtracted from each of these four values. The same was done when studying the evolution across collisions.

Sometimes, the correlation between two variables was investigated in order to determine whether or not they were dependent on each other. The Pearson correlation coefficient was then used.

These statistical analyses were performed with the *scipy.stats* and *statsmodels.stats* packages from Python. Significance level was set to 5%.

3 Results

3.1 Movement kinematics during one block

During one block, participants performed ten collisions towards the head and ten feetward collisions. A typical graph represents the position of the manipulandum center during an entire block in right-side-up orientation with eyes open in Figure 7. In this specific block, the subject first did two feetward collisions, then three headward collisions, after that one feetward collision, etc.

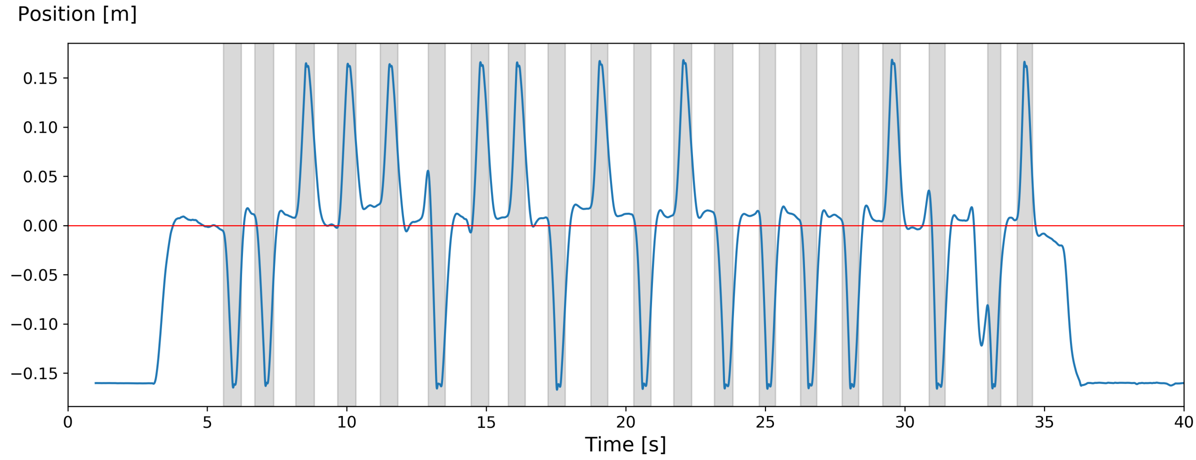

Figure 7: Typical manipulandum position profile during one block in right-side-up posture with eyes open. The red line represents the middle point between the two targets. Collisions zones are represented by gray areas.

The corresponding velocity profile is represented in Figure 8. As explained in section 2.4, the movement onset of each collision is defined based on velocity and the corresponding movement end is time-locked after impact. Both movement onset and end are represented by the bounds of the gray zones. Consistently with the position profile, we can observe that the subject first performed two feetward collisions as the velocity for these collisions first dropped to negative values, then three headward collisions with a velocity that increased to positive values after movement onset, etc.

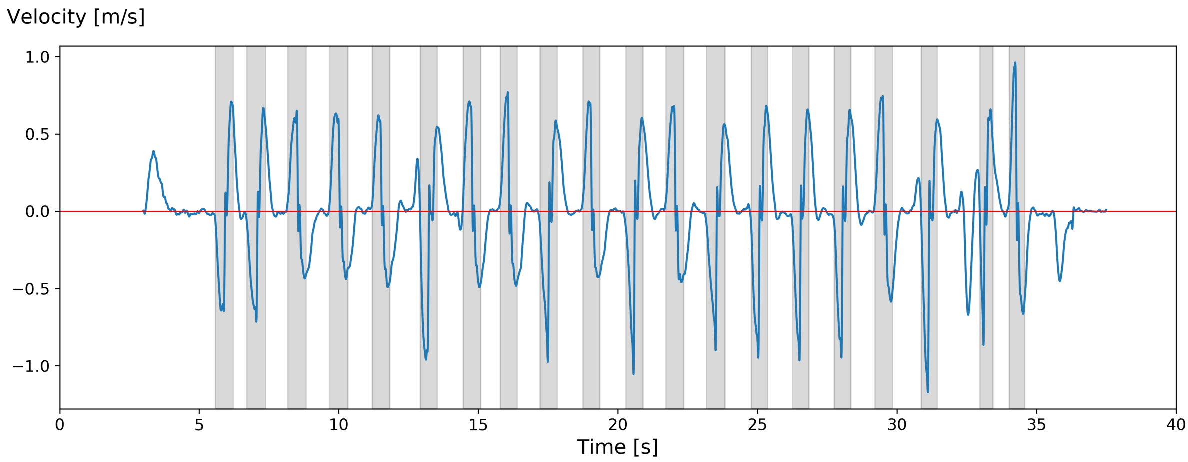

Figure 8: Typical manipulandum velocity profile during one block in right-side-up posture with eyes open. The red line represents the zero axis. Collisions zones are represented by gray areas.

The associated acceleration profile is shown in Figure 9 where the maxima of acceleration during each collision phase are illustrated by red points. These acceleration maxima are due to the impact of the manipulandum against targets.

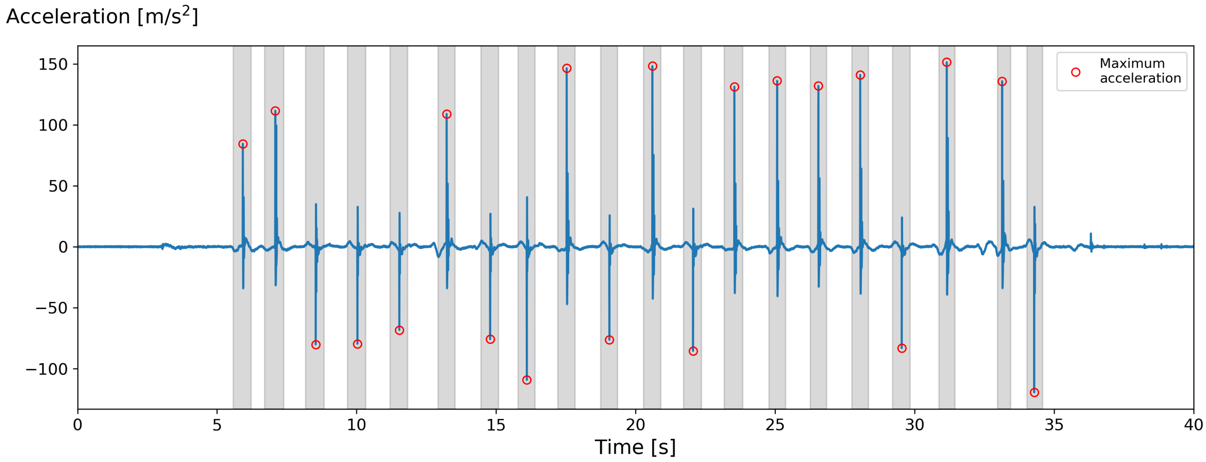

Figure 9: Typical manipulandum acceleration profile during one block in right-side-up posture with eyes open. Acceleration signal comes from high-G accelerometer. Red points represent the maximum of acceleration during collision phase. Collisions zones are represented by gray areas.

3.2 Load force and grip force profiles during one block

The Figure 10 shows the evolution of load and grip forces along time for the same block as the one presented in Figures 7, 8 and 9. The peaks of load forces are due to the impact. The grip force seems to be related to the load force evolution.

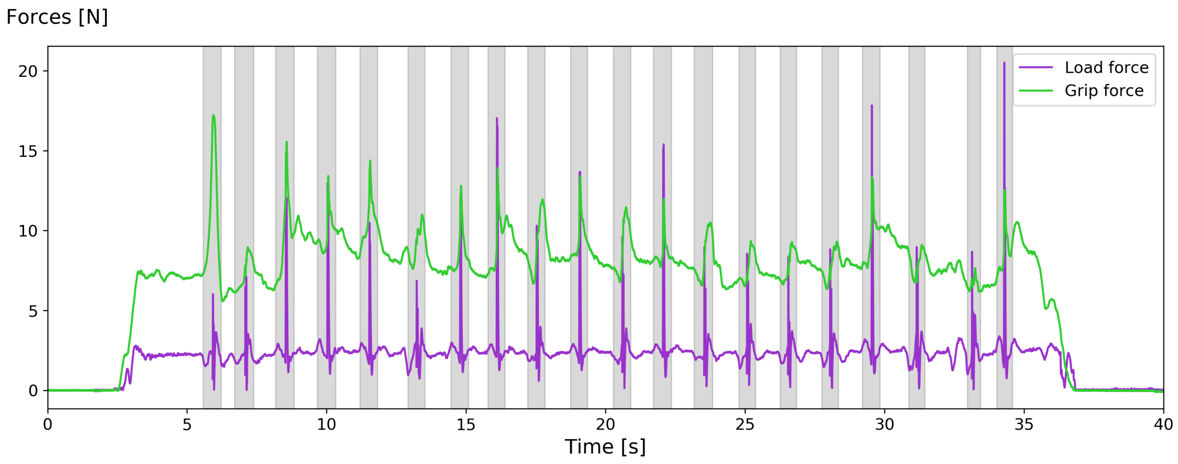

Figure 10: Typical forces profile during one block in right-side-up posture with eyes open. Load and grip forces are respectively represented by a purple and a green curve. Collisions zones are represented by gray areas.

3.3 Times of interest

Different times of interest can be defined when analyzing one specific collision, shown in Figures 11 and 12. We focus here on a feetward collision but the same times are defined for headward movements.

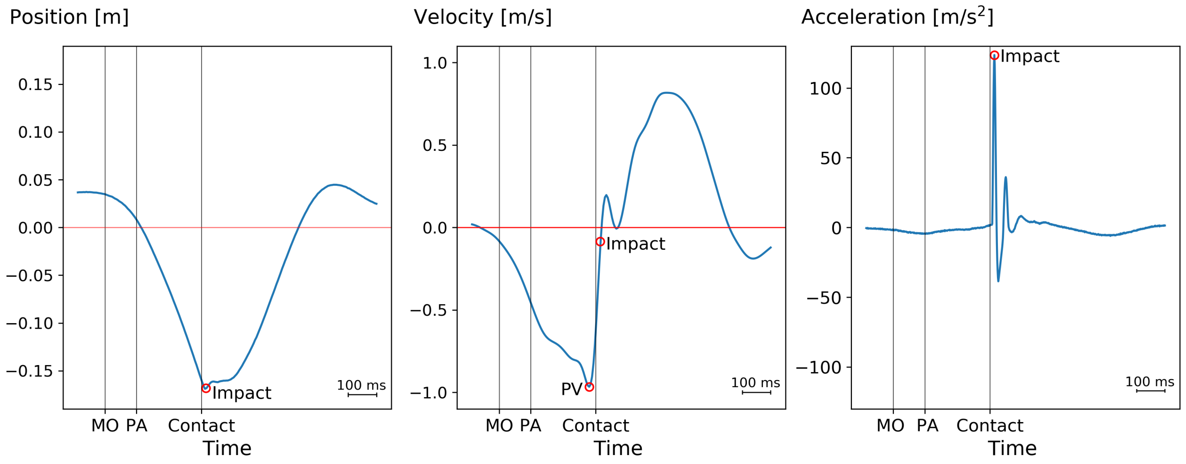

Figure 11: Typical kinematics profiles (position, velocity and acceleration) for one feetward collision in right-side-up posture with eyes open. The red lines represent the zero axis, or the middle point between the two targets for the position graph. Movement onset (MO), peak acceleration (PA) and contact time are represented by the left, middle and right cursors respectively. Peak velocity (PV) and impact time are represented by red dots.

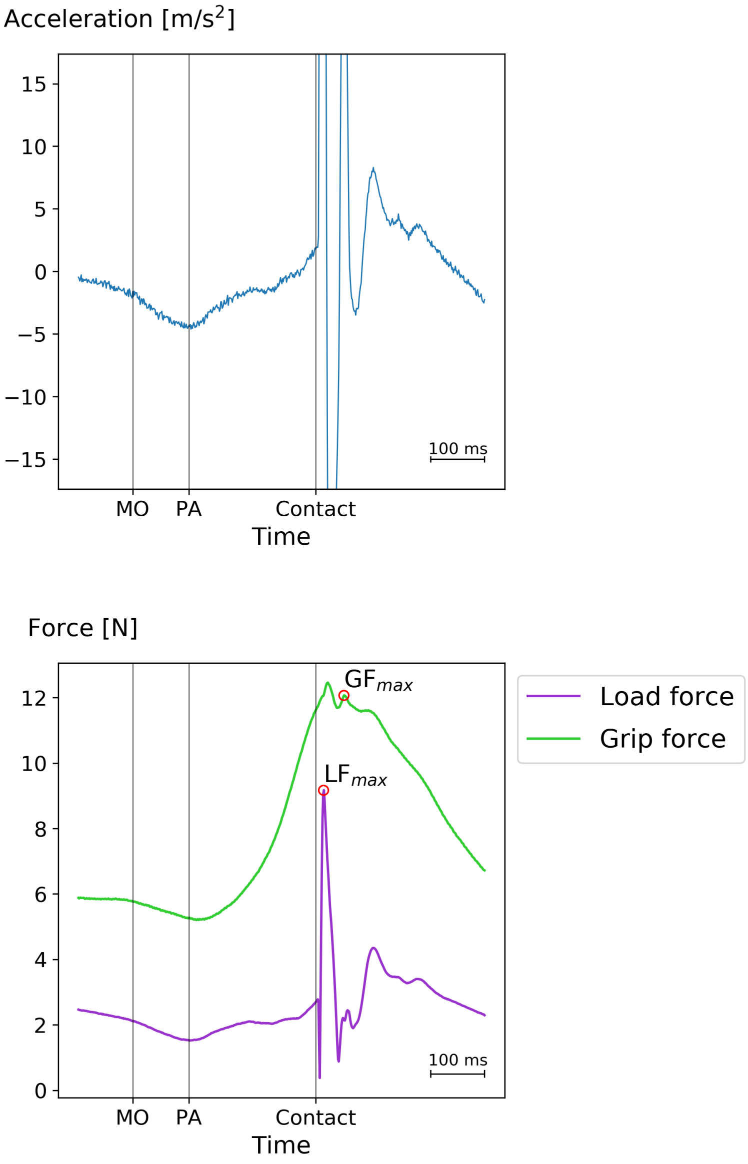

Figure 12: Typical acceleration and forces profiles for one feetward collision in right-side-up posture with eyes open. Load and grip forces are respectively represented by a purple and a green curve. Movement onset (MO), peak acceleration (PA) and contact time are represented by the left, middle and right cursors respectively. Maximum forces are represented by red dots.

Movement can be decomposed into two phases, the transport phase and the collision phase.

This first phase happens before the collision, when subjects move their hand towards the target. Figure 11 shows that for a feetward collision, the position during this transport phase is decreasing until the impact. Concerning the velocity, it has a bell-shaped profile. The object is accelerated towards the feet, the load force varies gently and thus the grip force evolves in parallel with the anticipated load force to keep an appropriate object stabilization. There is a coupling between the load and the grip forces during this transport phase. Then, the collision phase begins. In order to anticipate the impact, the grip force increases before the shock.

Firstly, movement onset, occurring 311 ± 28 ms before the impact, is represented in Figures 11 and 12.

The second noteworthy time is the peak acceleration. It is the time at which the absolute value of the acceleration is maximum, in an interval between movement onset and 100 ms before impact.

The velocity profile also exhibits an interesting time, represented in the middle panel of Figure 11 by a red dot. As a matter of fact, the peak velocity arises during transport phase, when the absolute value of the velocity is maximum.

The collision phase starts at the contact time, defined as occurring 15 ms before the impact. It corresponds approximately to the beginning of the acceleration peak related to the impact, thus, to the time when acceleration signal changes abruptly. It is represented in Figures 11 and 12. At this time, velocity increases steeply to zero. It is then shortly positive because of the damping of the foam target. This contact time is very noteworthy since it gives information about the programmed part of kinematics and grip force. Grip force at contact ($\mathrm{GF}_{contact}$) can be interpreted as the programmed grip force. It is the grip force that subjects programmed in anticipation of the collision.

A fifth time of interest is the impact time. It is defined as the moment when the absolute value of acceleration is maximum, which occurs before the peak of load force. One can notice that for this feetward collision, the maximum of acceleration is positive. Indeed, the subject's hand moves from a negative velocity to a null velocity in a short time period. At this time, load force changes significantly and there is no more coupling between grip and load forces. Approximately 100 ms after the impact time, the vertical position increases before stabilizing more or less between the two targets (see left panel of Figure 11).

A final time of interest is the moment when grip force reaches its maximum value. We defined it as the peak of grip force occurring at least 20 ms after the impact and at most 200 ms after the impact. As a matter of fact, considering this interval of time could allow overlooking the load force artifacts of the collision while remaining in a reasonably short zone after collision [18].

3.4 Kinematics

In the following sections, the behavior of a specific variable across all conditions will be compared. In the graphs presenting those results, blue triangles represent the average of the variable of interest for headward collisions while red ones are for feetward movements. Empty triangles represent the experimental condition for eyes open whereas solid triangles represent trials that were performed with eyes closed. Note that evolution across collisions and blocks will also be studied.

3.4.1 Start position of the hand and resulting movement amplitude

It can be observed in Figure 13 that the subjects' hand start position was not between the two targets, but slightly above the center (closer to the participants' head). Therefore, the movement amplitude, which is a consequence of the start position, was not equal when comparing headward and feetward collisions. This movement amplitude represents the difference between the manipulandum position at movement onset and at impact time. If subjects perfectly replaced the manipulandum between the two targets, movement amplitude should be equal to 16.45 cm. Surprisingly, it was on average greater for the feetward than for the headward collisions (main effect of Direction: $F_{1,17} = 24.74$, $p = 0.0001$). Indeed, for this first collision direction, the amplitude was on average equal to 17.50 ± 0.70 cm while it was equal to 15.79 ± 0.88 cm for movements towards the head.

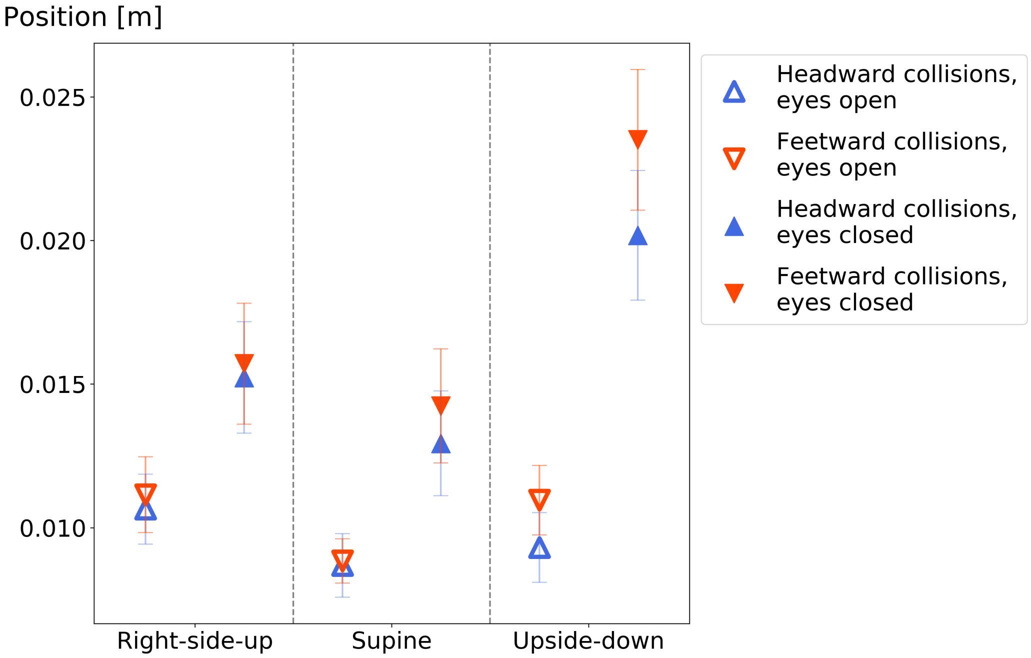

Figure 13: Start position means for headward and feetward collisions in all conditions across all subjects (n = 18). The headward and feetward collisions are separated and illustrated by blue and red triangles respectively. The eyes open and closed conditions are illustrated by empty and solid triangles respectively. Error bars represent standard error.

In each posture condition, the start position represented in Figure 13 was always more off-center with eyes closed than with eyes open (main effect of Vision: $F_{1,17} = 38.37$, $p < 0.0001$). Therefore, for each posture, it can be observed that the amplitude difference between headward and feetward collisions was always greater for the eyes closed condition compared with the corresponding eyes open condition. The interaction between vision and direction on amplitude was statistically significant (Direction:Vision: $F_{1,17} = 15.88$, $p = 0.001$). Both headward and feetward collisions were initiated further from the center when subjects closed their eyes ($t_{17} = 2.61$, $p = 0.018$ and $t_{17} = -4.54$, $p = 0.0003$ respectively). And this difference between vision conditions was even more pronounced in the upside-down position. When subjects performed movements with eyes closed in this latter, the amplitude was equal to 14.93 ± 1.23 cm for headward collisions while it was equal to 18.66 ± 1.65 cm for feetward collisions. Also, the standard deviation of the start position was larger when participants had their eyes closed rather than open (standard deviation varied between 0.80 and 1.0 cm in the eyes closed condition whereas it varied between 0.40 and 0.53 cm in the eyes open condition, with the largest standard deviation in the upside-down position with eyes closed).

Additionally, concerning amplitude, posture and direction factors interacted together (Posture:Direction: $F_{2,34} = 5.36$, $p = 0.009$). When collisions were performed towards the head, amplitude was significantly lower if subjects were upside-down compared to supine ($t_{34} = 4.89$, $p = 0.0004$). But if they were performed towards feet, it was then greater in the upside-down orientation than in the supine posture ($t_{34} = -2.95$, $p = 0.03$). Neither for headward nor for feetward movements was the amplitude different in right-side-up versus upside-down or right-side-up versus supine postures (t_{34} varied between -1.66 and 1.54, all $p > 0.3$).

3.4.2 Time-to-impact

Strikingly, even if movement amplitude was higher for feetward than for headward collisions, the time between movement onset and impact, and thus the movement duration, was generally longer for headward collisions (main effect of Direction: $F_{1,17} = 6.87$, $p = 0.02$). The headward time-to-impact equalled 316.72 ± 23.73 ms whereas it was 305.44 ± 33.59 ms for feetward collisions. This can be observed in Figure 14.

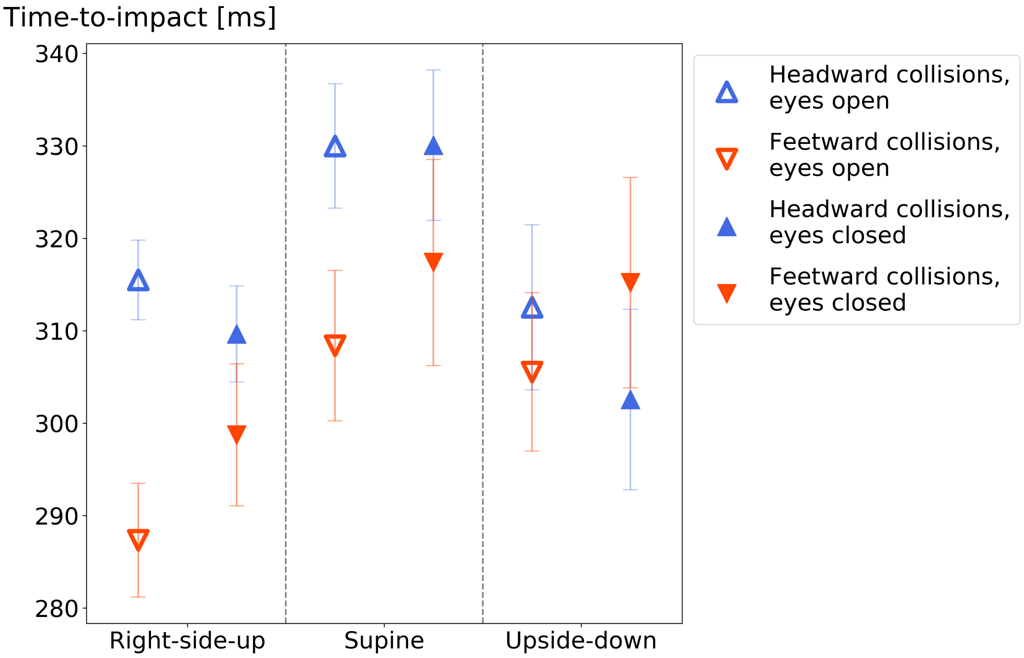

Figure 14: Means of the time between movement onset and impact (time-to-impact) for headward and feetward collisions in all conditions across all subjects (n = 18). The headward and feetward collisions are separated and illustrated by blue and red triangles respectively. The eyes open and closed conditions are illustrated by empty and solid triangles respectively. Error bars represent standard error.

Furthermore, subjects' posture interacted with movement direction (Posture:Direction: $F_{2,34} = 7.48$, $p = 0.002$). In the right-side-up and supine orientations, movement lasted longer in the case of headward collisions compared with feetward collisions ($t_{17} = 3.31$, $p = 0.004$ and $t_{17} = 3.15$, $p = 0.006$ respectively). But in the upside-down orientation, the time-to-impact was not statistically different between headward and feetward movements ($t_{17} = -0.50$, $p = 0.6$).

Besides, there was a significant cross-effect between movement direction and vision (Direction:Vision: $F_{1,17} = 12.0$, $p = 0.003$). While subjects took on average the same time to perform headward collisions whether they opened or closed their eyes ($t_{17} = 1.59$, $p = 0.13$), feetward collisions lasted longer when they closed their eyes ($t_{17} = -2.78$, $p = 0.01$).

In a nutshell, subjects always placed the manipulandum not in the middle of the two targets but a little bit higher, towards their heads. And this effect was even more pronounced when they were upside-down with eyes closed. In doing so, their movement's amplitude was smaller for headward than feetward collisions but participants surprisingly took more time in general to reach the target located towards their head. Obviously, these effects were accentuated when subjects closed their eyes.

3.4.3 Manipulandum tilt

It is interesting to note that the manipulandum was tilted at impact. As a matter of fact, the angle of this latter was calculated in the sagittal plane. To ease the comparison in all conditions, the absolute value of this angle was taken. This angle was equal to $4.72 \pm 1.31°$ for headward collisions while it was statistically higher for feetward collisions (main effect of Direction: $F_{1,17} = 66.23$, $p < 0.0001$). Indeed, in those latter collisions, the manipulandum was tilted at $14.61 \pm 4.97°$.

3.4.4 Velocity

Remarkably, peak velocity (PV) and contact velocity ($V_{contact}$) had higher absolute values for feetward than for headward collisions, whichever the condition. This can be observed in Figure 15.

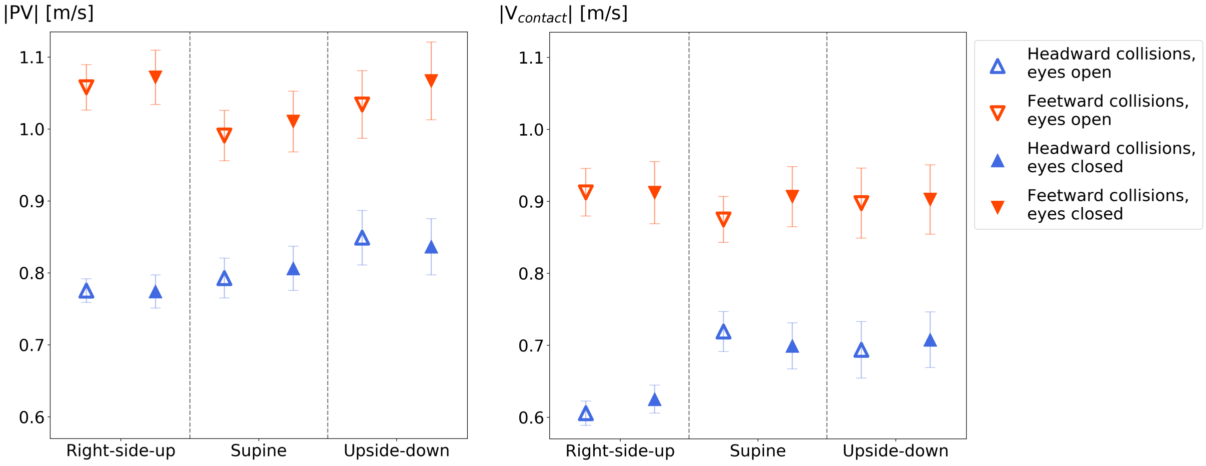

Figure 15: Means of the absolute value of peak velocity (PV, left panel) and velocity at contact ($V_{contact}$, right panel) for headward and feetward collisions in all conditions across all subjects ($n = 18$). The headward and feetward collisions are separated and illustrated by blue and red triangles respectively. The eyes open and closed conditions are illustrated by empty and solid triangles respectively. Error bars represent standard error.

Indeed, for velocity at contact, movement direction was the only significant main effect (main effect of Direction: $F_{1,17} = 312.91$, $p < 0.0001$). This velocity was on average equal to 0.90 ± 0.16 m/s for collisions towards the feet. And it was significantly higher whichever the position than for headward collisions where $V_{contact}$ was equal to 0.68 ± 0.11 m/s. Furthermore, there was a statistical interaction between posture and direction (Posture:Direction: $F_{2,34} = 15.25$, $p < 0.0001$). On the one hand, velocity at contact for feetward collisions varied statistically in the same range across the different postures (t_{34} varied between -0.3 and 0.68, all $p > 1.5$). On the other hand, in the case of headward collisions, contact velocity was lower in the right-side-up position than in the supine and upside-down postures ($t_{34} = -4.30$, $p = 0.001$ and $t_{34} = -2.78$, $p = 0.04$

respectively). Contact velocity in these last two orientations did not differ significantly (t_{34} = 0.43, p = 2.01).

Note that the ANOVA did not report a significant main effect of vision ($F_{1,17}$ = 1.25, p = 0.3). Also, the intra-subject variability in contact velocity was not different between eyes open or closed conditions (t_{17} = -1.35, p = 0.2).

Concerning the peak velocity, as in the case of velocity at contact, it was significantly higher for feetward (1.04 ± 0.16 m/s) than for headward (0.81 ± 0.11 m/s) collisions (main effect of Direction: $F_{1,17}$ = 238.13, $p < 0.0001$). Direction also interacted with posture (Posture:Direction: $F_{2,34}$ = 12.96, p = 0.0001). But whether during headward or feetward collisions, peak velocity was the same across the three subjects' orientations (t_{34} varied between -2.22 and 2.55, p varied between 0.06 and 1.94). And here again, peak velocity did not differ whether subjects opened or closed their eyes ($F_{1,17}$ = 3.08, p = 0.1).

Velocity across blocks

There was no significant effect of vision on contact velocity and vision interacted neither with posture (Posture:Vision: $F_{2,34}$ = 0.05, p = 0.96), nor with movement direction (Direction:Vision: $F_{1,17}$ = 0.56, p = 0.5). Therefore, the evolution of velocity at contact across the four blocks represented in Figure 16 is computed for the two vision conditions together. Peak velocity exhibited a similar profile, but with larger values.

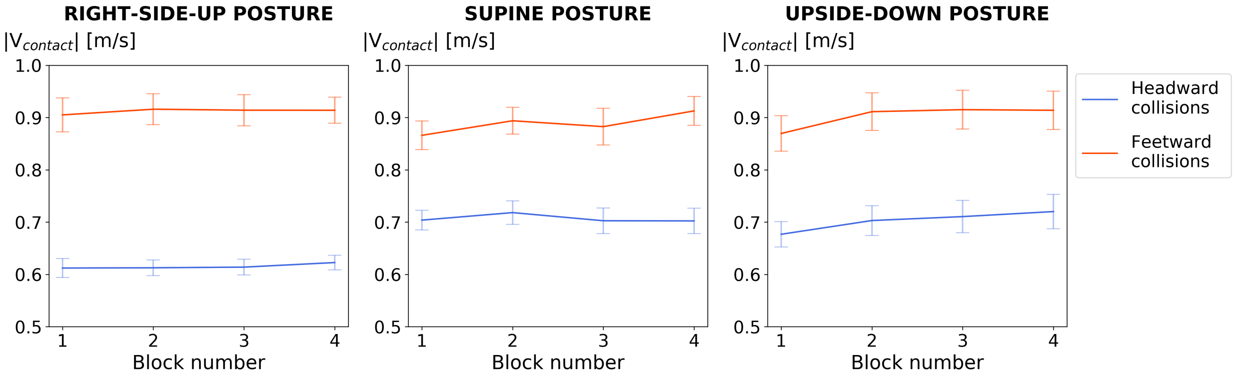

Figure 16: Evolution of the means of the absolute value of velocity at contact ($V_{contact}$) in right-side-up (left panel), supine (middle panel) and upside-down (right panel) postures in the four blocks across all subjects (n = 18) with eyes open or closed. The headward and feetward collisions are separated and illustrated by blue and red curves respectively. Error bars represent standard error.

With two exceptions, contact velocity was stable across the four blocks (t varied between -0.07 and 1.96, all $p > 0.05$ except in upside-down position where t = 2.57, p = 0.01 and

$t = 2.50$, $p = 0.01$ respectively for headward and feetward collisions).

Regarding peak velocity, it remained constant across all the blocks in right-side-up and supine posture (t varied between -0.23 and 1.81, all $p > 0.07$). In the upside-down position, peak velocity increased for headward collisions ($t = 2.47$, $p = 0.02$) but not for feetward movements ($t = 1.65$, $p = 0.1$). However, the difference between feetward and headward peak velocities stayed stable whichever the subjects' posture (t varied between -0.9 and 1.38, all $p > 0.1$).

Time-to-peak-velocity

The time-to-peak-velocity (TPV) is defined as the duration from movement onset to peak velocity divided by the time between movement onset and impact. On average, the peak velocity arose about 72 to 89 % of the movement. This peak velocity occurred later when collisions were performed towards feet, meaning that the deceleration phase was shorter since the peak velocity took place closer to the contact time.

The time-to-peak-velocity was significantly affected by direction (main effect of Direction: $F_{1,17} = 78.81$, $p < 0.0001$). As a matter of fact, the time-to-peak-velocity was significantly higher for feetward compared with headward collisions in each posture (all $t_{17} < -2.27$, all $p < 0.04$). Of note, this TPV difference between collisions direction is affected by vision in the supine posture (Posture:Direction:Vision: $F_{2,34} = 11.75$, $p = 0.0001$). When subjects opened their eyes, time-to-peak-velocity did not statistically differ when comparing both directions ($t_{17} = -1.36$, $p = 0.2$). But when they closed it, this time was larger for feetward collisions regarding headward collisions ($t_{17} = -3.02$, $p = 0.008$).

Altogether, peak velocity and contact velocity showed that subjects were faster when moving towards their feet regardless of their position. Consistently, the time-to-peak-velocity was also greater for feetward collisions compared with headward collisions. Besides, these velocities did not evolve along blocks under almost all conditions.

3.5 Dynamics

To better analyze the effect of gravity on the forces applied on the manipulandum, in the first instance, the maximum of load force as well as the grip force at contact are analyzed in depth. Then, the fingers' centers-of-pressure will be studied. Finally, friction coefficient will be discussed in order to investigate the slip force and the safety margin.

3.5.1 Load force

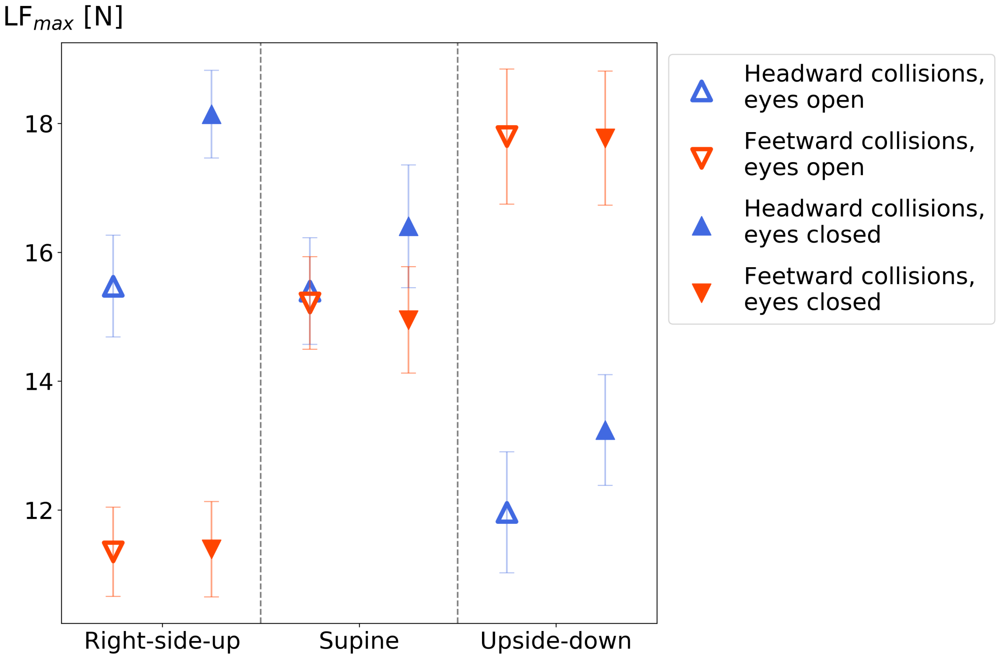

Figure 17: Load force maximum (LF_{max}) means for headward and feetward collisions in all conditions across all subjects (n = 18). The headward and feetward collisions are separated and illustrated by blue and red triangles respectively. The eyes open and closed conditions are illustrated by empty and solid triangles respectively. Error bars represent standard error.

Neither posture nor movement direction had a significant main effect on load force maximum, denoted as LF_{max} ($F_{2,34} = 3.06$, $p = 0.06$ and $F_{1,17} = 0.88$, $p = 0.36$ respectively). Nevertheless, vision factor had a significant effect on this load force (main effect of Vision: $F_{1,17} = 20.06$, $p = 0.0003$), which was higher in the eyes closed than open condition. This can be observed in Figure 17.

Furthermore, there was a statistically significant three-way interaction between posture, direction and vision (Posture:Direction:Vision: $F_{2,34} = 5.69$, $p = 0.007$). More specifically, there were significant cross-effects between posture and direction (Posture:Direction: $F_{2,34} = 156.0$, $p < 0.0001$), between posture and vision (Posture:Vision: $F_{2,34} = 3.88$, $p = 0.03$) and between direction and vision (Direction:Vision: $F_{1,17} = 33.51$, $p < 0.0001$).

Regarding interactions between posture and direction, LF_{max} was statistically greater for headward than for feetward movements in the right-side-up orientation whereas it was the opposite in the upside-down posture ($t_{17} = 9.34$, $p < 0.0001$ and $t_{17} = -11.15$, $p < 0.0001$ respectively). Indeed, this latter had a profile opposite to the right-side-up position due to a gravitational bias. During headward collisions, the inertial component makes a positive contribution when a movement is performed right-side-up while it makes a negative contribution to load force when being upside-down. And during feetward collisions, the acceleration term is subtracted or added from the gravitational term when being right-side-up or upside-down respectively. However, in the supine orientation, maximum of load force was statistically the same whichever the collision direction ($t_{17} = 1.64$, $p = 0.12$). Here, gravity had the same influence for headward and feetward collisions. More accurately, this load force maximum was on average the same between headward and feetward collisions in the supine condition with eyes open ($t_{17} = 0.36$, $p = 0.72$) while it was greater for headward than feetward collisions in the eyes closed condition ($t_{17} = 2.56$, $p = 0.02$).

It would be noteworthy to compare LF_{max} from an allocentric point of view. Whether considering movements towards the sky or towards the ground, the maximum of load force was not statistically different between right-side-up and upside-down postures ($t_{17} = -0.98$, $p = 0.34$ when comparing headward collisions in right-side-up orientation with upside-down feetward collisions; $t_{17} = -2.09$, $p = 0.05$ when comparing feetward collisions in right-side-up orientation with upside-down headward collisions). This seems rational since gravity has then the same impact on headward than feetward load forces. More precisely, load force maximum in movements pointing towards the sky was equal to 17.30 ± 3.16 N while for movements in the opposite direction, LF_{max} equalled 11.99 ± 3.13 N. Note that in the supine position, this load force was equal to 15.49 ± 3.27 N.

The impact of vision on load force maximum is interesting. The difference of load force between eyes open and closed condition was not statistically significant in supine position ($t_{17} = -1.10$, $p = 0.29$). It was only in the right-side-up and upside-down postures that this effect was significant ($t_{17} = -7.87$, $p < 0.0001$ and $t_{17} = -2.16$, $p = 0.04$ respectively). As a matter of fact, in these two positions, LF_{max} with the eyes closed were greater than with eyes open. Surprisingly, it was actually for the collisions towards head that this effect was the most visible. As observed in Figure 17, LF_{max} was greater for a collision towards the head if subjects closed their eyes (regarding the eyes open condition) whereas subjects hit the target located towards their feet with the same range of load force whether their eyes were open or closed. Thus, vision had a strong impact on the maximum of load force for collisions towards the head ($t_{17} = -5.42$, $p < 0.0001$) while it did not significantly impact feetward collisions ($t_{17} = 0.72$, $p = 0.48$).

Load force across blocks

Another interesting point is the evolution of load force maximum across the four blocks. This force value remained constant across blocks (no significant main effect of Block on LF_{max}: $F_{3,51} < 0.8$, $p > 0.5$ in the three postures). Moreover, the block factor had no significant interaction with vision (Block:Vision: $F_{3,51} < 1.6$, $p > 0.2$ in the three postures), nor with collision direction (Block:Direction: $F_{3,51} < 1.8$, $p > 0.1$ in the three postures). What is more, the slope of the linear least-squares regression in each condition was never statistically different from zero (t varied between -1.64 and 1.1, all $p > 0.11$).

Delay between impact acceleration and maximum load force

Quite remarkably, load force maximum always arose later than impact acceleration (see Figure 29 in Appendices). Even more interestingly, this time was significantly shorter in the case of feetward collisions compared with headward collisions (main effect of Direction: $F_{1,17} = 59.18$, $p < 0.0001$). While it was equal to 2.41 ± 1.02 ms for collisions towards the feet, it was equal to 9.24 ± 3.88 ms in the case of headward collisions.

Of note, this time was larger when subjects closed their eyes than when they opened it (main effect of Vision: $F_{1,17} = 36.46$, $p < 0.0001$).

All in all, subjects' maximum load force was higher when they performed movements against gravity, i.e. headward and feetward collisions when being right-side-up and upside-down respectively, than when they performed movements following gravity. If subjects were supine, they applied relatively the same maximum load force. But it should be noted that, in all postures, their load force was always higher for headward collisions with eyes closed than with eyes open while this was not observable for feetward collisions. Additionally, this maximum load force, which arose after the impact acceleration, did not evolve across blocks.

3.5.2 Grip force

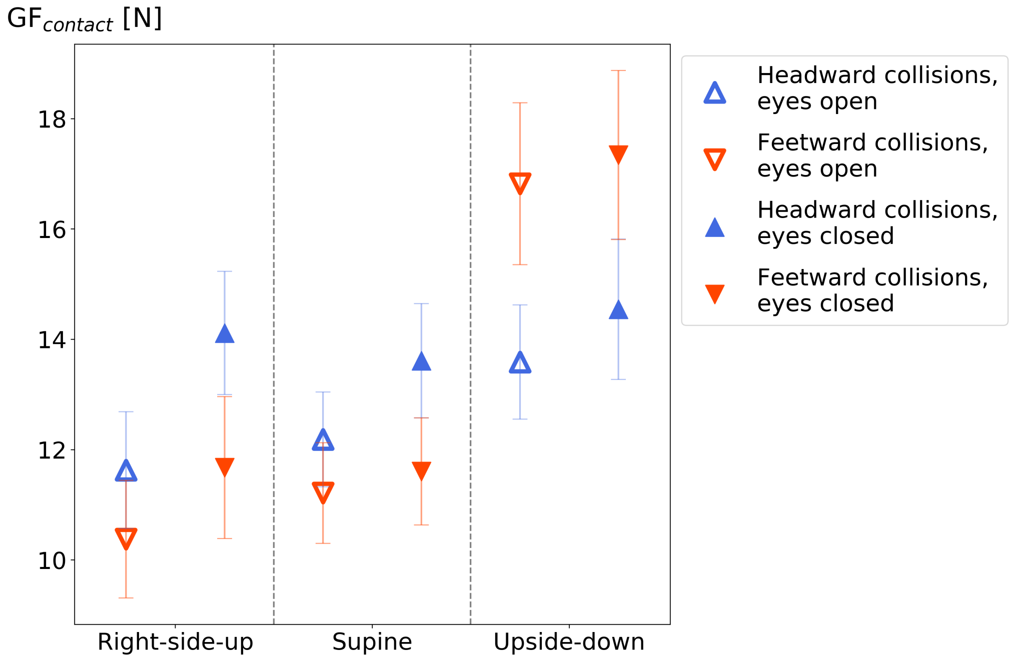

Figure 18: Grip force at contact (GF$_{contact}$) means for headward and feetward collisions in all conditions across all subjects (n = 18). The headward and feetward collisions are separated and illustrated by blue and red triangles respectively. The eyes open and closed conditions are illustrated by empty and solid triangles respectively. Error bars represent standard error.

Concerning contact grip force, as observed in Figure 18, it was significantly affected by the posture (main effect of Posture: $F_{2,34} = 15.74$, $p < 0.0001$). Indeed, GF$_{contact}$ in upside-down posture was significantly higher than in right-side-up and in supine positions (t_{34} = -4.68, p = 0.0006 and t_{34} = -4.51, p = 0.0009 respectively). In contrast, the grip force was not statistically different between the right-side-up and the supine postures (t_{34} = -0.32, p = 2.25). More specifically, for respectively the right-side-up, the supine and the upside-down postures, grip force at contact was equal to 11.95 ± 4.57 N, 12.15 ± 3.78 N and 15.57 ± 5.42 N.

Moreover, there was a significant interaction between posture and direction (Posture:Direction: $F_{2,34} = 22.72$, $p < 0.0001$). Grip force at contact was significantly greater for headward collisions than for feetward collisions in the right-side-up and supine orientations, while it was significantly smaller for headward than feetward collisions in the upside-down position (t_{17} = 2.96, p = 0.009; t_{17} = 3.18, p = 0.005 and t_{17} = -4.39, p = 0.0004 respectively). More specifically concerning the supine posture, GF$_{contact}$ did not differ between headward and feetward collisions when participants opened their eyes (t_{17} = 2.04, p = 0.06) while it was greater for headward than feetward collisions when they closed their eyes (t_{17} = 4.10, p = 0.0007).

If grip force at contact is compared allocentrically, one can observe that for collisions towards sky, $GF_{contact}$ was higher when subjects were upside-down than right-side-up (t_{17} = -3.92, p = 0.001). The same applied for collisions towards ground (t_{17} = -4.68, p = 0.0002).

Another interesting parameter is the effect of vision. It had a significant main effect on the grip force at contact values (main effect of Vision: $F_{1,17}$ = 12.53,p = 0.003). These later were greater when collisions were performed with eyes closed than when they were performed with eyes open. Besides, there was also a significant cross-effects between vision and direction (Direction:Vision: $F_{1,17}$ = 20.11, p = 0.0003). For headward collisions, grip force at contact was significantly greater when subjects closed their eyes compared to when they had their eyes open (t_{17} = -4.70, p = 0.0002). Nonetheless, this effect was not significant for feetward movements (t_{17} = -2.10, p = 0.05).

All these observations about $GF_{contact}$ also applies for the maximum of grip force (GF_{max}). The only difference is that grip force maximum values were approximately 3 N greater. Indeed, grip force at contact was on average equal to 13.22 ± 4.29 N while GF_{max} was equal to 16.13 ± 5.30 N.

Grip force at contact evolution across blocks

The $GF_{contact}$ evolution across the four blocks is represented in Figure 19 in the right-side-up, supine and upside-down postures. For each block of each subject in each condition, the mean of contact grip force of the twenty collisions was computed. Then, the average of this mean across the eighteen subjects and the associated standard error were calculated. Each graph shows the evolution of headward or feetward collisions, in eyes open and closed condition.

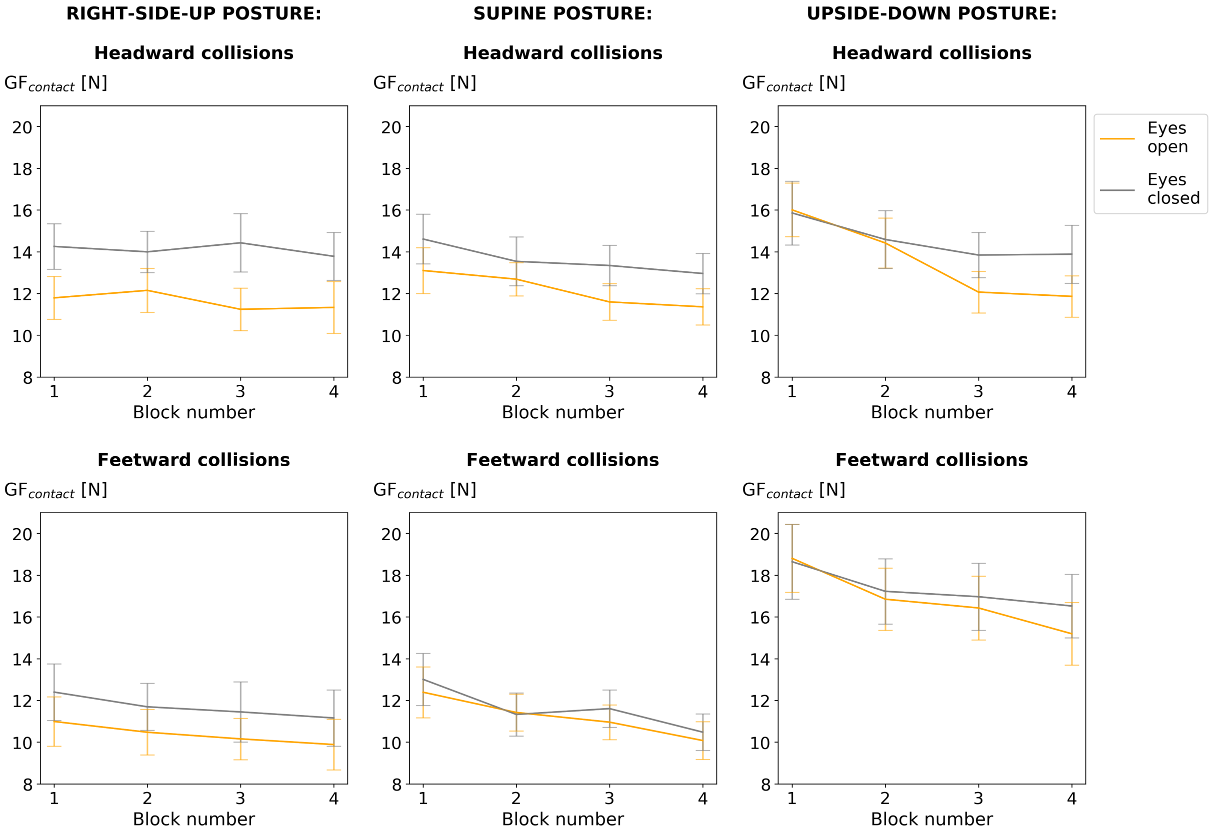

Figure 19: Evolution of grip force at contact (GF$_{contact}$) means in right-side-up (left column), supine (middle column) and upside-down (right column) postures for headward (top graphs) and feetward (bottom graphs) collisions in the four blocks across all subjects ($n = 18$). The eyes open and closed conditions are separated and illustrated by orange and gray curves respectively. Error bars represent standard error.

Firstly, concerning right-side-up posture, it can be noticed in Figure 19 that grip force at contact remained stable across the four blocks when subjects performed headward collisions ($t = -1.97$, $p = 0.05$ and $t = -0.66$, $p = 0.5$ for the eyes open and closed condition respectively). Surprisingly, this grip force decreased across blocks in the case of feetward collisions ($t = -2.32$, $p = 0.02$ in eyes open condition and $t = -3.05$, $p = 0.003$ in eyes closed condition).

Secondly, when subjects were supine, GF$_{contact}$ was significantly decreasing in all conditions (all $t < -3.81$, all $p < 0.0002$). This is observed in the middle column in Figure 19.

Thirdly, the grip force evolution in upside-down position (see right column Figure 19) exhibited quite the same behavior as in supine position. GF$_{contact}$ decreased significantly across blocks whether participants opened or closed their eyes (all $t < -2.76$, all $p < 0.007$).

To summarize, when subjects were right-side-up or supine, they grasped the manipulandum harder for collisions towards their head. In the upside-down posture, it was the opposite and their grip force at contact was higher for feetward collisions. As the load force, grip force was higher in the eyes closed than open condition and this effect was actually more pronounced for collisions towards the head. It should be noted that grip force at contact for the upside-down orientation was much higher regarding the two other positions. Concerning the evolution across blocks, $GF_{contact}$ decreased in all conditions except when subjects performed feetward collisions in the right-side-up posture.

Grip force at movement onset

The grip force at movement onset (GF_{onset}), represented in Figure 30 in the Appendices, was affected among others by the posture (main effect of Posture: $F_{2,34} = 18.66$, $p < 0.0001$). Similarly to $GF_{contact}$, when being upside-down, subjects gripped the manipulandum harder than when being right-side-up or supine ($t_{34} = -4.84$, $p = 0.0005$ and $t_{34} = -4.64$, $p = 0.0007$ respectively). However, they gripped similarly the manipulandum in the right-side-up and supine orientations ($t_{34} = -1.14$, $p = 0.8$).

Contrarily to $GF_{contact}$, the ANOVA test did not reveal any interaction between direction and vision for grip force at movement onset (Direction:Vision: $F_{1,17} = 2.63$, $p = 0.1$).

On another note, participants' posture interacted with their movement direction (Posture:Direction: $F_{2,34} = 26.93$, $p < 0.0001$). Participants gripped similarly in both directions when they were upside-down ($t_{17} = -1.86$, $p = 0.08$), whereas they gripped statistically harder towards their head than their feet in the two other postures ($t_{17} = 6.47$, $p < 0.0001$ in right-side-up position and $t_{17} = 3.53$, $p = 0.003$ in supine position).

In summary, grip force at movement onset was also greater when subjects were upside-down than when they were right-side-up or supine, as it was the case of $GF_{contact}$. And in upside-down orientation, GF_{onset} was similar independently of collision direction while it was larger for headward than feetward collisions in the right-side-up and supine positions.

Time between contact and grip force maximum

Grip force reached its maximum value 74.72 ± 7.76 ms after contact. Curiously, this time was about 20 ms latter in the case of feetward than headward collisions (main effect of Direction: $F_{1,17} = 17.50$, $p = 0.0006$). Grip force was maximum approximately 64.77 ± 12.04 ms after contact when subjects performed headward collisions, and 84.67 ± 13.39 ms after contact for feetward collisions.

Note that there was a statistical correlation between the time at which GF_{max} was reached and the value of GF_{max}, but it was very weak ($r = -0.08$, $p = 0.02$). Grip force had a slight tendency to exhibit a lower maximum value when it occurred latter. There was also a statistical correlation between the time at which GF$_{max}$ was reached and the contact velocity (r = 0.16, p < 0.0001). This correlation was positive but weak.

3.5.3 Center-of-pressure

The centers-of-pressure (COP) of the thumb and index finger are calculated separately in Equations 3 and 4. They depend on normal force (F_y), tangential forces (F_x and F_z), associated torques (T_x and T_z) and parameters. These latter represent the thickness of moisture sensor and the distance between manipulandum and sensor origin. The first one, δ in the equations, is equal to 1.55 mm while the second one, ϵ, is equal to 18.75 mm.

For the left sensor (thumb):

$$CoP_x = \frac{T_z - F_x \cdot (\delta + \epsilon)}{F_y} \qquad CoP_z = -\frac{T_x + F_z \cdot (\delta + \epsilon)}{F_y} \tag{3}$$

For the right sensor (index finger):

$$CoP_x = -\frac{T_z + F_x \cdot (\delta + \epsilon)}{F_y} \qquad CoP_z = \frac{T_x - F_z \cdot (\delta + \epsilon)}{F_y} \tag{4}$$

The centers-of-pressure represent the location of the thumb and index finger on the manipulandum. It shows how fingers are centered in the middle of each sensor. The evolution of these centers-of-pressure across the collisions during one block is an interesting parameter. Indeed, it is not unusual to observe slippage during a collision, leading to a fingers displacement on the manipulandum. A collision can also lead to a finger pad deformation, without slippage. As a matter of fact, the finger skin is not rigid. Center-of-pressure being the resultant of the point of application of the forces, if the finger pad is deformed, the application point of the forces will be displaced.

To see how a collision influences fingers position, we looked at the centers-of-pressure during the static phase before each collision. This static phase was defined as going from 100 to 50 ms before movement onset. For each subject, before each collision, the mean of the COP on the vertical axis during this phase was computed. The COP evolution across collisions is shown in Figures 20, 22 and 24. The vision had no significant effect on these values (all $F_{1,17} < 1.1$, all p > 0.3). And except for the index finger when subjects were right-side-up (main effect of Direction: $F_{1,17} = 8.39$, p = 0.01), the movement direction had no significant effect either (all $F_{1,17} < 1.6$, all p > 0.1). Therefore, graphs are shown for eyes open and closed conditions, and for headward and feetward collisions together.

A first observation was that when holding the manipulandum, the thumb and index finger were not aligned. Indeed, it was observed in right-side-up orientation that index finger was placed higher than thumb (Figure 20). Quite remarkably, the same finger configuration was kept in both supine and upside-down postures. This is shown in Figures 22 and 24, but also in Figures 21, 23 and 25 where the misalignment represents the difference between the center-of-pressure of the index finger and the one of the thumb.

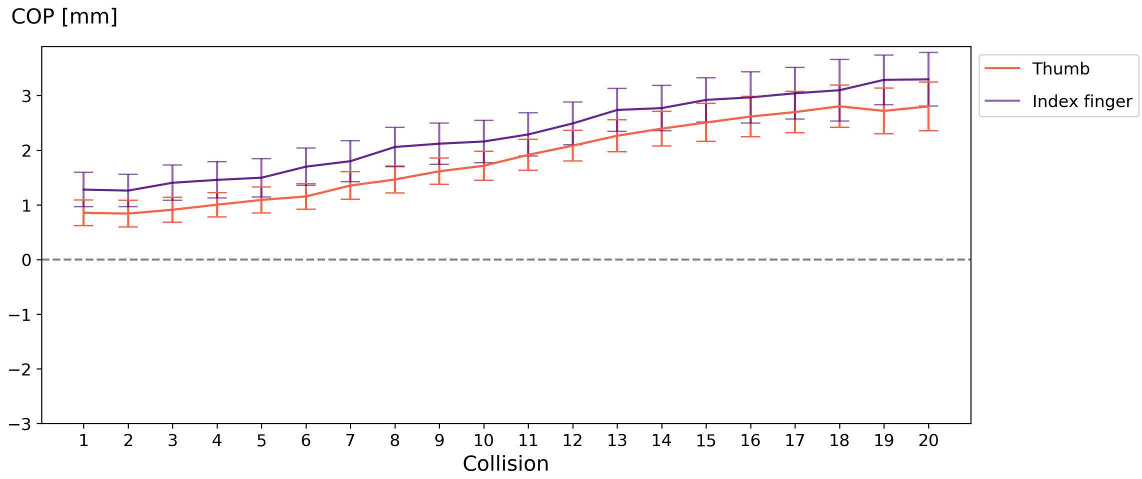

Figure 20: Evolution of centers-of-pressure (COP) means of the thumb and index finger along vertical axis during static phase in right-side-up posture across all subjects (n = 18). Orange and purple curves represent the thumb and index finger respectively. Error bars represent standard error.

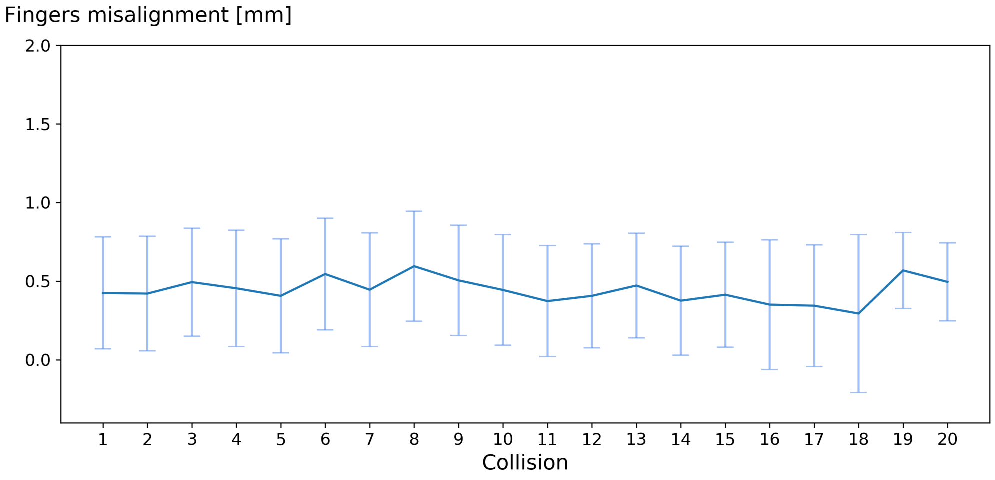

Figure 21: Evolution of misalignment means between thumb and index finger along vertical axis in right-side-up posture across all subjects (n = 18). Error bars represent standard error.

Secondly, in the right-side-up position, the fingers were more and more off-centered as illustrated in Figure 20. Indeed, the slope of the linear regression was significantly positive for both fingers (t = 19.08 for the thumb and t = 18.23 for the index finger, both $p < 0.0001$). That is coherent with the greater load force for headward than feetward collisions in this posture because of the gravity impact. Indeed, centers-of-pressure went up because fingers displacement towards the sky during headward collisions was greater than fingers displacement towards the ground occurring in feetward collisions. Furthermore, one can notice in Figure 21 that in this usual subjects' position, the misalignment decreased slightly across the twenty collisions (t = -3.34, p = 0.0009), resulting in a tiny fingers realignment.

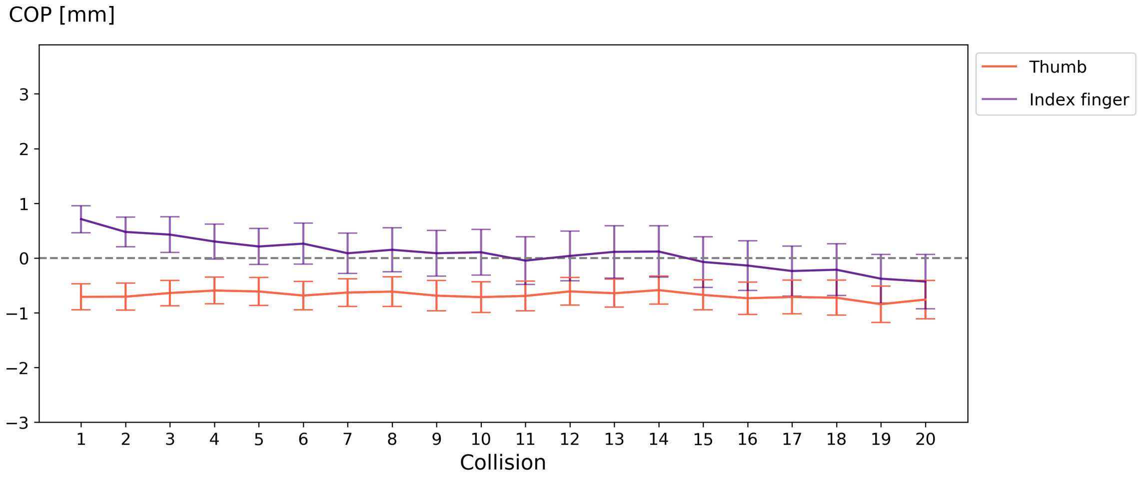

Figure 22: Evolution of centers-of-pressure (COP) means of the thumb and index finger along vertical axis during static phase in supine posture across all subjects (n = 18). Orange and purple curves represent the thumb and index finger respectively. Error bars represent standard error.

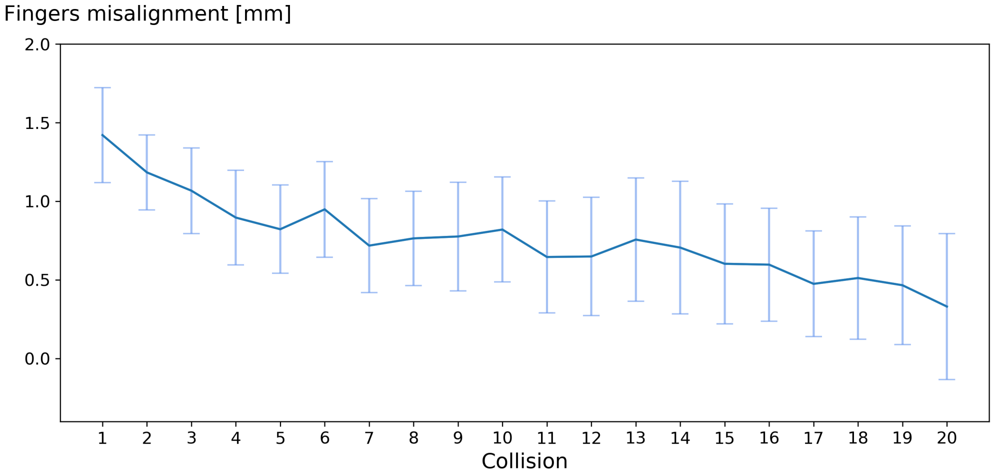

Figure 23: Evolution of misalignment means between thumb and index finger along vertical axis in supine posture across all subjects (n = 18). Error bars represent standard error.

When being supine, Figure 22 shows that the thumb position did not significantly move (t = -1.16, p = 0.2) while the index finger tended to join the thumb position (t = -8.57, $p < 0.0001$). The result of this was that the fingers misalignment tended to decrease across collisions (the slope of the misalignment curve was significantly negative: t = -7.87, $p < 0.0001$, see Figure 23).

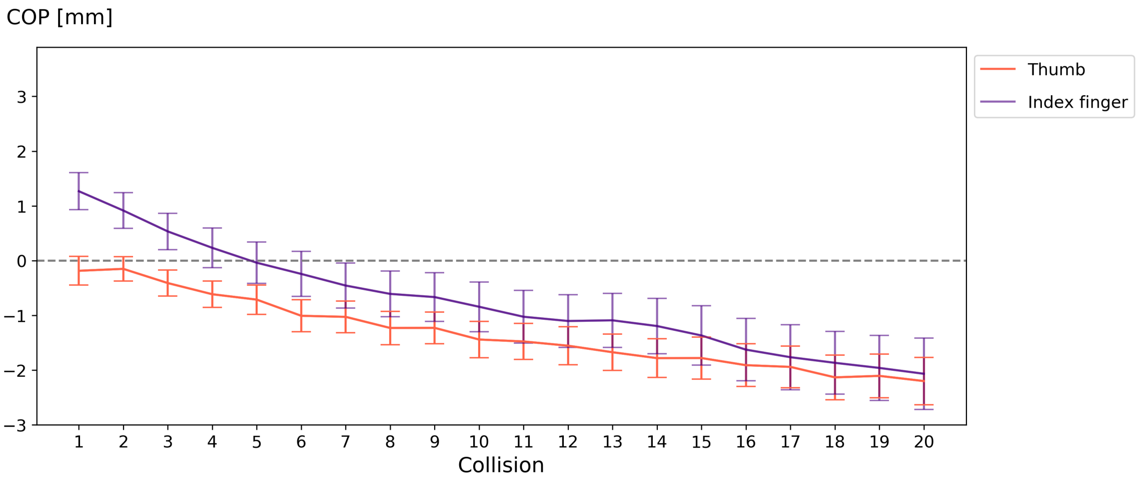

Figure 24: Evolution of centers-of-pressure (COP) means of the thumb and index finger along vertical axis during static phase in upside-down posture across all subjects ($n = 18$). Orange and purple curves represent the thumb and index finger respectively. Error bars represent standard error.

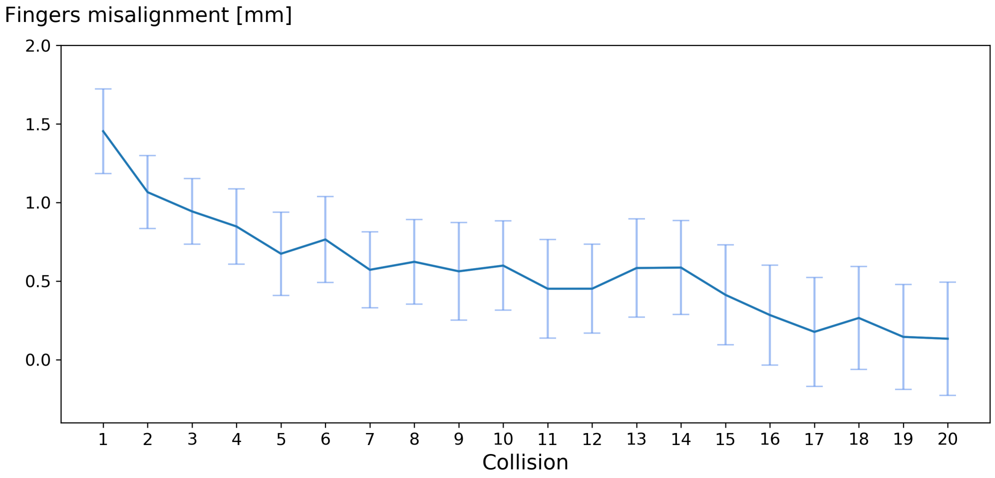

Figure 25: Evolution of misalignment means between thumb and index finger along vertical axis in upside-down posture across all subjects ($n = 18$). Error bars represent standard error.

Regarding the upside-down posture, both fingers were less and less centered throughout collisions as outlined in Figure 24 (both slopes were statistically negative, $t < -22.31$, $p < 0.0001$). Indeed, the reverse logic than for the right-side-up orientation applies. Here, the COP positions were closer and closer to the manipulandum bottom since load force was here larger in the case of feetward than headward collisions. Nevertheless, it can be observed in Figure 25 that the misalignment decreased across collisions ($t = -11.32$, $p < 0.0001$). As when subjects were supine, a realignment appeared to take place over collisions.

Whereas it was in the right-side-up orientation that the initial misalignment was the smallest with a value of 0.42 ± 0.36 mm (mean ± standard error), it was in the upside-down posture that the smallest fingers misalignment was reached after twenty collisions (0.13 ± 0.36 mm, mean ± standard error).

3.5.4 Friction coefficient

The friction coefficient plays a major role in determining the normal force that subjects have to apply on an object in order to keep it stable. Indeed, the higher the friction, the smaller the normal force that has to be applied. Note that this friction coefficient is influenced by skin moisture.

Here, the friction coefficient of thumb and index finger was measured separately before and after experiments in each position. For each of these postures, data collected before and after the blocks were grouped together for the computation of the coefficient of friction since the three-factors ANOVA (on rub direction, finger and time) did not report a statistical difference between these two time measurements ($F_{1,17} = 3.74$, $p = 0.07$). Moreover, headward and feetward rub movements were distinguished because, when going headwards or feetwards, the friction coefficient was different. It was indeed larger when subjects rubbed towards the manipulandum top than towards its bottom (main effect of Direction: $F_{1,17} = 15.87$, $p = 0.001$). Therefore, for each subject, four friction coefficients per position were computed. Two per finger and two per rub direction. Note that the three-way ANOVA was done by grouping together the three postures, since a one-way ANOVA did not report a main effect of posture ($F_{2,34} = 2.76$, $p = 0.08$).

Strikingly, friction coefficient was greater for thumb than for index finger (main effect of Finger: $F_{1,17} = 7.76$, $p = 0.01$).

3.5.5 Slip force

The slip force (SF) is the minimal normal force that would prevent slippage. It is defined in Equation 5 and depends on the tangential force (TF) and two specific parameters (k and n). They are measured or calculated from the coefficient of friction test that participants had to perform at the beginning and at the end of each experienced position, as describe in section 2.2.3.

$$SF = \left(\frac{TF}{k}\right)^{\frac{1}{n}} \tag{5}$$

As explained just above (section 3.5.4), the distinction was done between headward and feetward coefficients of friction. The slip force of headward (feetward) collisions was thus computed based on the parameters k and n extracted from headward (feetward) coefficient of friction. Slip force was taken as the maximum between the slip force exerted on thumb and the one exerted on index finger.

The slip force was smaller in the case of collisions towards ground than towards sky ($t_{17} = 7.91$, $p < 0.0001$).

On another note, this force was larger when subjects closed their eyes than when they opened it (main effect of Vision: $F_{1,17} = 5.63$, $p = 0.03$). Also, movement direction factor interacted with vision factor (Direction:Vision: $F_{1,17} = 4.62$, $p = 0.05$). Indeed, whereas slip force was larger in eyes closed condition than in eyes open condition in the case of headward collisions ($t_{17} = -2.27$, $p = 0.04$), it was not statistically different for feetward collisions ($t_{17} = -0.65$, $p = 0.5$).

Slip force did not exhibit an evolution across the four blocks (t varied between -1.91 and 1.05, all $p > 0.06$), except in the right-side-up orientation when participants performed feetward collisions with eyes open ($t = -2.1$, $p = 0.04$).

3.5.6 Safety margin

The safety margin (SM) is defined, in Equation 6, as the difference between the exerted normal force (NF) and the slip force (SF), normalized by this slip force.

$$SM = \frac{NF - SF}{SF} \tag{6}$$

Here, we took the normal force exerted at contact to have an idea of the safety margin that is planned by subjects just before the collision. It is therefore not impacted by an artifact due to the collision. The mean value of this safety margin was equal to 0.15 ± 0.44. It was thus smaller than the safety margin computed by taking the normal force at the time when tangential force, and thus slip force, was maximal (0.30 ± 0.49). Most of the following results would also applied if the safety margin was computed with the normal force at the time of maximal tangential force, unless specified otherwise.

The minimum between the safety margin of thumb and of index finger was taken. It was indeed important to compute this safety margin for each finger separately since we saw in section 3.5.3 that there was a misalignment between the thumb and index finger, leading to a tangential force that was not equally distributed between these two fingers. The normal force for its part was not statistically different between thumb and index finger ($t_{17} = 1.21$, $p = 0.2$).

The following graphs were computed in the same way as the one about the contact grip force evolution presented in section 3.5.2, in order to better analyze the safety margin evolution.

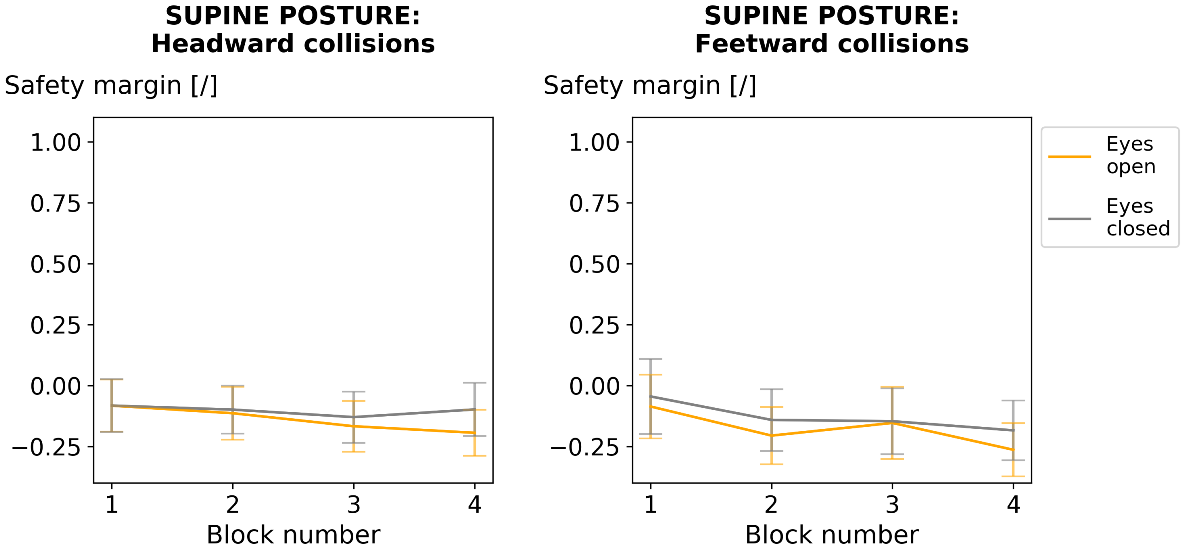

Figure 26: Evolution of safety margin means for headward (left panel) and feetward (right panel) collisions in the four blocks across all subjects (n = 18) when they were supine. The eyes open and closed conditions are separated and illustrated by orange and gray curves respectively. Error bars represent standard error.

When being supine, safety margin was neither affected by collision direction nor by vision ($F_{1,17} = 0.16$, $p = 0.7$ and $F_{1,17} = 1.56$, $p = 0.2$ respectively). It was only affected by the block factor (main effect of Block: $F_{3,51} = 5.03$, $p = 0.004$). More precisely, while the slope of the linear regression across blocks was not statistically different from zero in the eyes closed condition for headward collisions ($t = -0.62$, $p = 0.5$), it was statistically decreasing for all the others conditions ($t < -2.94$, $p < 0.004$). This can be observed in Figure 26.

One can also notice that safety margin was on average negative in this position (-0.14 ± 0.45). Note that when the safety margin was computed at the time when tangential force is maximum, it was only negative for feetward collisions and not for headward collisions.

Regarding the right-side-up and the upside-down orientations, the safety margin was compared in an allocentric reference frame so that the impact of gravity is the same. Quite remarkably, safety margin was greater in the case of collisions towards ground than towards sky ($t_{17} = -5.61$, $p < 0.0001$).

Firstly, collisions towards head in right-side-up orientation and the ones towards feet in upside-down posture are compared in Figure 27. In these two conditions, subjects performed collisions against gravity and their safety margin was on average equal to 0.02 ± 0.32.

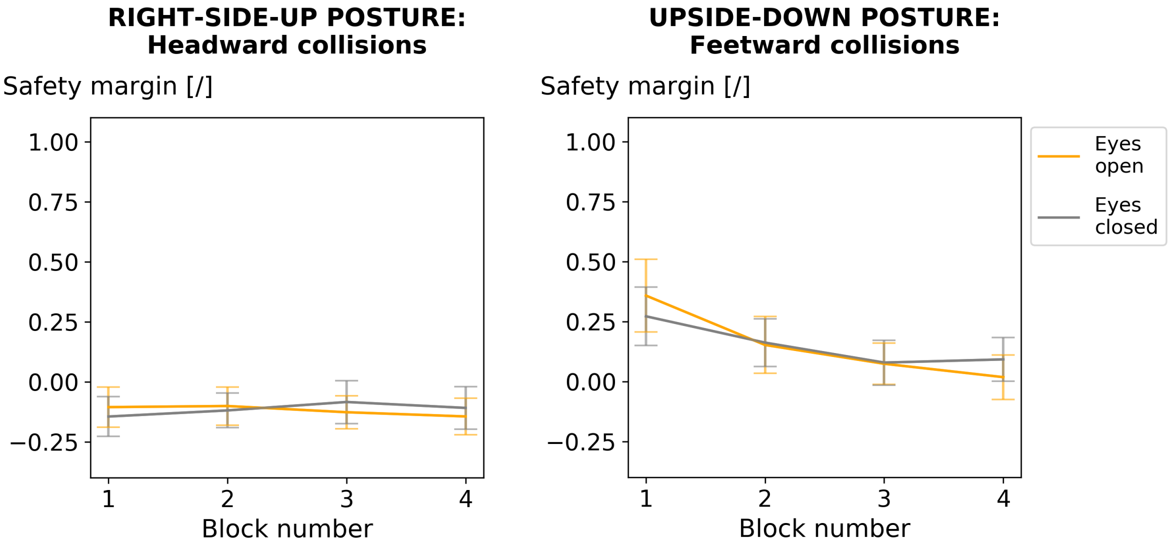

Figure 27: Evolution of safety margin means for headward collisions in right-side-up posture (left panel) and for feetward collisions in upside-down posture (right panel) in the four blocks across all subjects (n = 18). The eyes open and closed conditions are separated and illustrated by orange and gray curves respectively. Error bars represent standard error.

Curiously, vision did not have a main effect on safety margin ($F_{1,17} = 0.01$, $p = 0.9$) for these skyward collisions.

On another note, the block factor affected safety margin (main effect of Block: $F_{3,51} = 4.37$, $p = 0.008$). More specifically, this factor interacted with posture (Block:Posture: $F_{3,51} = 7.14$, $p = 0.0004$). On the one hand, in upside-down posture, safety margin decreased statistically across blocks for both eyes open and closed conditions (slope statistically negative: $t < -3.61$, $p < 0.0005$). On the other hand, it stayed stable across the four blocks in the case of collisions performed right-side-up ($t = -1.24$, $p = 0.2$ for eyes open condition and $t = 0.91$, $p = 0.4$ for eyes closed).

Note that safety margin was negative in the case of headward collisions performed right-side-up (this was not the case for the safety margin computed at the time where tangential force was maximum).

Secondly, collisions towards the feet in right-side-up orientation are compared with the ones towards the head in upside-down posture in Figure 28. In both conditions, collisions were directed in the same direction as gravity. The safety margin was then equal to 0.56 ± 0.65.

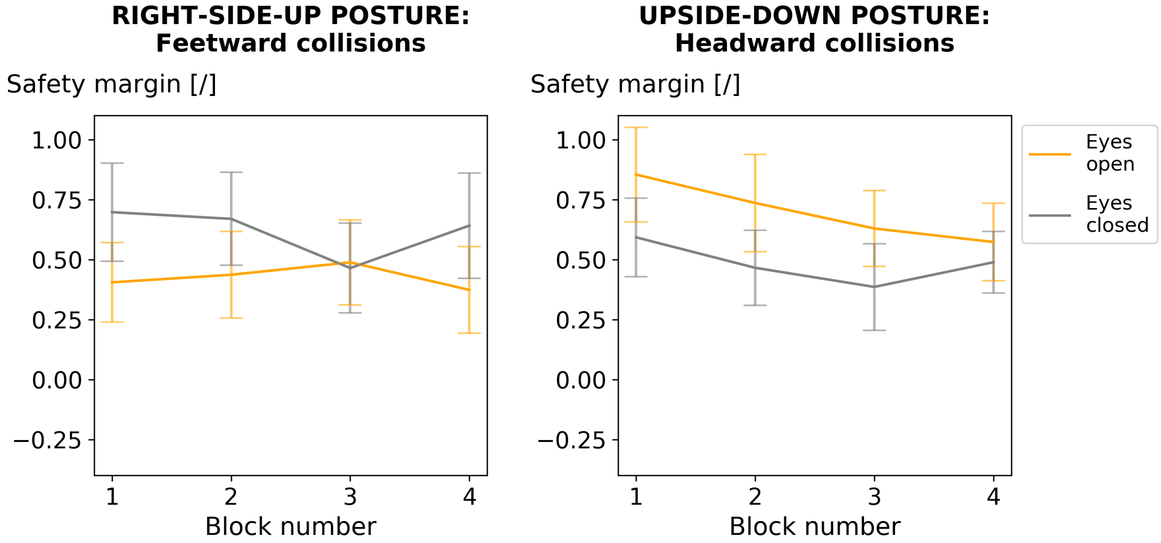

Figure 28: Evolution of safety margin means for feetward collisions in right-side-up posture (left panel) and for headward collisions in upside-down posture (right panel) in the four blocks across all subjects (n = 18). The eyes open and closed conditions are separated and illustrated by orange and gray curves respectively. Error bars represent standard error.

None of the vision, posture or block factors had a main effect on safety margin ($F_{1,17} = 0.09$, $p = 0.77$; $F_{1,17} = 0.35$, $p = 0.56$ and $F_{3,51} = 2.16$, $p = 0.10$ respectively). However, an interaction between vision and posture existed (Posture:Vision: $F_{1,17} = 16.98$, $p = 0.0007$). While safety margin was statistically larger in the eyes closed compared with the eyes open condition when being right-side-up (t_{17} = -3.86, $p = 0.001$), it was the opposite when being upside-down ($t_{17} = 2.93$, $p = 0.009$).

When participants performed headward collisions in upside-down orientation with eyes open, safety margin decreased according to blocks ($t = -2.39$, $p = 0.02$). In the three other conditions, safety margin stayed constant (all $t < -0.2$, all $p > 0.18$).

Note that when headward and feetward collisions were considered together, as it can be observed in Figure 31 in Appendices, safety margin was larger when participants were upside-down than when they were supine ($t_{34} = -6.14$, $p < 0.0001$) and than when they were right-side-up, but not significantly ($t_{34} = -2.56$, $p = 0.06$). At the time when tangential force reached its maximum, this latter difference between upside-down and right-side-up safety margin was significant ($t_{34} = -2.69$, $p = 0.047$).

In a nutshell, when subjects were supine, they planned a safety margin that varied globally in the same range of values. More interestingly, it was on average always negative. Surprisingly, safety margin in this right-side-up posture for headward collisions was also negative. Regarding vision, while it did not affect safety margin when collisions were going against gravity, it had an effect for collisions going along gravity. For these groundward collisions, when they were right-side-up, subjects planned a higher safety margin for collisions performed with eyes closed than open while it was the opposite when being upside-down. Concerning the evolution across blocks of the safety margin, it stayed stable when subjects were right-side-up or when they performed headward collisions with eyes closed in supine or upside-down posture. In all other conditions, it decreased along blocks.

4 Discussion

During arm movements when holding an object, prediction is essential in order to keep a proper object stability, especially in case of collisions. The modulation of forces applied by the precision grip is a strong indicator of prediction control provided by the internal model.

Studies about collisions under normal and different gravity conditions have already evidenced anticipatory adjustments of grip force [3, 17, 18]. Also, oscillatory and discrete movements were investigated under altered gravitational environments such as microgravity or hypergravity by various authors [1, 5, 6, 15]. During oscillatory movements, the tight coupling between grip force and load force demonstrated the predictive control of grip force. This latter is performed in an allocentric reference frame [15]. Other authors demonstrated that during pointing movements, arm kinematics could also vary with the visual information when being supine, leading to an allocentric or egocentric reference frame depending on the vision condition [13]. These previous studies withstanding, grip force control and adaptation during collisions have been less extensively studied.

Here, we evaluated the effect of gravity on predictive mechanisms in collisions tasks. In our study we asked participants to perform collisions in three different positions representing three different gravity conditions with their eyes open or closed. Discussion of the reference frame under which kinematics and grip dynamics were planned will be discussed hereafter.

4.1 Kinematics are planned in an egocentric reference frame

4.1.1 Start position of the hand

The fact that the start position was slightly above the center for both feetward and headward collisions and thus that the amplitude was greater for feetward versus headward collisions is possibly due to an optical effect. Indeed, the eye level was higher than the targets center, which was approximately at shoulder level. Therefore, subjects may have thought they were aiming for the center while being a little too high due to the angle of vision. It is also possible that unconsciously, they tended to place their hand in front of their eyes instead of in front of their shoulder. These seems likely since in each posture, this effect was accentuated when participants closed their eyes.

Also, when in an upside-down position, participants had generally a more off-centered start position than when being supine. This may reflect the fact that the upside-down position is more unusual than the supine position, which is a posture we experience every day, for instance when lying on a bed. Thus, when being upside-down, spatial orientation is impaired and subjects may have more difficulties to center the manipulandum. Another possible justification is that participants were closer to the target oriented towards their head when being upside-down. Indeed, despite the presence of straps, subjects were slightly off the seat. This probably made them start the collisions closer to their head.

Additionally, the start position of the movement was the most off-centered in upside-down orientation with eyes closed. It is also in this condition that the start position variability was the largest. It is not surprising since it is the most unusual position. Subjects may have more difficulties to replace their hand in the middle of the two targets, and to place it at the same position before each collision, explaining the largest feetward amplitude and the smallest headward amplitude for this uncommon condition.

Besides, the larger amplitude of feetward collisions regarding headward collisions may partially explain that the manipulandum was more tilted for these collisions. Indeed, it was maybe more difficult to keep the manipulandum vertical on a longer distance, leading to a larger tilt at the end of the trajectory in the case of feetward collisions.

4.1.2 Time-to-impact

It may seem surprising that, during experiments, movement duration was on average longer for headward than feetward collisions. We might have expected to observe the inverse phenomenon since the amplitude was smaller for these headward collisions. Nevertheless, movement duration depends on velocity profile. Headward peak velocity was smaller than feetward peak velocity. Consequently, in the right-side-up and supine positions, even if a shorter distance was covered in the case of headward movements, it took longer because of the smaller peak velocity. Nonetheless, time-to-impact was not longer for headward compared with feetward collisions when subjects were upside-down. In this case, it was statistically the same whether the collision was performed towards head or feet. However, both amplitude and peak velocity were larger for feetward collisions. As a matter of fact, feetward collisions were of larger amplitude, but they were performed more quickly whereas headward collisions were slower but a smaller distance was covered. On the whole, movement duration was therefore the same. Note that the same reasoning does not apply for the supine position for example where the start position is lower than in upside-down posture, so where the difference between headward and feetward amplitude was smaller. For the supine posture, it is then the velocity that is of greater importance to explain the difference in time-to-impact between headward and feetward collisions.

The fact that feetward movement duration was larger with eyes closed than with eyes open is arguably related to the fact that feetward movements exhibited a larger amplitude in the eyes closed condition than in the open one while the peak velocity was identical between the two vision conditions.

4.1.3 Velocity

The velocity at contact is a reliable parameter since it does not contain noisy information related to the collision itself. This velocity is a parameter among other factors influencing the shock intensity since it is linked to the quantity of energy that has to be absorbed. Indeed, kinetic energy has to be absorbed at the impact time. Importantly, this contact velocity is controlled by the participant (consciously or unconsciously).

Unexpectedly, contact velocity was observed to be similar between eyes open and closed condition. We were expecting to see smaller contact velocity when subjects closed their eyes as they could be more afraid of the object slipping and they could less predict the collision time. Yet, participants seemed to stay confident with eyes closed since contact velocity did not differ whether they opened or closed eyes. What is more, the intra-subjects' variability in contact velocity did not differ whether their eyes were open or closed, meaning that participants seemed to adopt a rather similar behavior in both vision conditions.

Strikingly, it appears that kinematics were reproduced independently of gravity since we observed that peak velocity and velocity at contact were always larger for feetward than headward collisions. This implies that the arm kinematics were programmed in an egocentric referential. Subjects reproduced the same velocity profile, even if they were supine or upside-down. Perhaps, whether consciously or not, when being right-side-up, subjects felt the risk of slippage was higher for headward than for feetward collisions. This prior that headward collisions are more risky may have been carried over to the other body postures because of the preponderance of the alignment of headward and skyward directions in everyday life. Additionally, one could assume that participants did not have enough sensory signals to realize that there was a risk of dropping the manipulandum. Sensory signals might be more difficult to extract during collisions. As an impact is extremely brief and significant, it could be postulated that some sensory receptors saturated at this time. This saturation could have led to less precise information about the impact intensity. This is different from discrete movements where the natural update of the internal model is easier. There is continuity in the multisensory signals in these movements, which differs from the impulse response due to a sudden collision. Furthermore, since none of the subjects dropped the object during experiments, they may not have been aware of the real risk of falling. Even if there was sometimes a centers-of-pressure displacement as presented in section 3.5.3, it was about 3 mm, so very small, and it did not lead subjects to drop the manipulandum. Due to this lack of sensory information, subjects may have limited cues to realize that some collisions were more risky than others. The above reasons could explain why we did not observe the expected kinematics adjustment in the supine and upside-down postures.

Compared to what was observed in oscillatory movements by Opsomer and his colleagues (2021), peak velocity in our results did not adapt along blocks, except in the upside-down posture for headward collisions. They pointed out in one of their experiments that a readjustment of the difference between peak velocity in the two movement directions was taking place, while it was not the case in our results. Another difference with Opsomer's results is that, before adaptation, they had larger headward than feetward peaks velocity in both right-side-up and upside-down orientations [15]. In our study, we had exactly the opposite. We propose two hypotheses that could explain why we did not observe any peak velocity adaptation and more surprisingly, that our results were opposite to those of Opsomer and collaborators concerning the direction. Firstly, in our experiments, subjects experienced two vision conditions instead of one. Alternating between collisions with and without vision could slow down collisions' adaptation. After only one block performed with eyes open, subjects had to close their eyes for the next block, preventing them from experiencing an adaptation. Secondly, our experiments consisted in collisions and not in oscillatory movements. Contrarily to oscillations, collisions are characterized by a risk of slippage that depends on the movement direction. As a matter of fact, headward collisions are more prone to accidental slips than feetward collisions in the right-side-up posture. The lack of adaptation could be related to different adaptation rates between two completely different tasks. For oscillations, the adaptation may reflect an optimization of the trajectory. For collisions, one could expect an adaptation of the prior that headward collisions are more risky than feetward collisions. A longer adaptation could be required for collisions, which consist in a different task than oscillations. These assumptions about a slower adaptation could also emphasize the egocentric kinematics planning.

Time-to-peak-velocity

In the same vein as what we have just discussed about velocity, whichever the subjects' posture, time-to-peak-velocity was smaller for headward movements, as if subjects did not take into account gravity. As a consequence, the peak velocity always occurred closer to contact for feetward versus headward collisions. This correlates with the fact that peak velocity was smaller for headward collisions, because subject then began to decelerate earlier. Contrarily, for feetward collisions, the subjects began to decelerate later. Moreover, they decelerated less and their contact velocity was larger, although in the upside-down posture, the risk of falling was more important when colliding the feetward targets. This result of headward TPV arising before feetward TPV is coherent with Le Seac'h et al. (2007) observations on subjects that were right-side-up. Of note, in their paper, subjects performed pointing movements and not collisions [13]. This greater feetward than headward TPV in the three postures is in agreement with the egocentric planning of arm kinematics we discussed just above.

To summarize, the amplitude, peak velocity and contact velocity remained larger for feetward collisions in each position, which supports a planning in an egocentric reference frame for the kinematics control when performing collisions with a hand-held object.

4.2 Dynamics are based on a multimodal reference frame

Motor control is crucial to anticipate gravity effects on object manipulation. Participants had to perform collisions with an object against targets while ensuring an adequate object stabilization. During experiments, none of the subjects dropped the manipulandum. This indicates that their behavior was globally appropriate.

4.2.1 Load force

Load force, which acts tangentially on the contact fingers/object interface, can be broken down into two components under normal gravity condition: a gravitational term and an inertial term. For headward collisions in the right-side-up orientation, since the acceleration component made a positive contribution to load force, it was logical to observe higher load force for these headward movements compared with feetward collisions.

Contrarily, during headward collisions in the upside-down posture, the inertial component made a negative contribution to load force, explaining why load force was smaller for these collisions than for feetward collisions.

For the supine position, theoretically, because gravity made a constant contribution to load force, this latter should be the same whichever the movement direction. That was the case in the eyes open condition of our experiments. However, when participants closed their eyes, the mean load force towards the head was higher than for feetward collisions. The study of Le Seac'h and colleagues (2007) demonstrated similar results concerning the time-to-peak-velocity when participants were performing pointing movements. They observed that when subjects were reclined with their eyes open, there were no asymmetries for discrete head-feet movements. Nonetheless, when participants closed their eyes, the asymmetries were again observed [13]. Thereby, a similar phenomenon was observed in our results, not with discrete movements but for the dynamics of collisions.

Load force maximum is related to centers-of-pressure

Moreover, load force maximum is linked to the centers-of-pressure. Indeed, LF_{max} impacts the centers-of-pressure evolution. If load force is higher for one specific collision direction, fingers will be more and more off-center. As a matter of fact, load force maximum was higher for movements going towards the sky in right-side-up and upside-down posture and it was in those specific postures that fingers' centers-of-pressure appeared to evolve the most. Centers-of-pressure evolution along one block was affected by gravity. In the right-side-up orientation, load force maximum was higher for headward than feetward collisions and then, fingers' centers-of-pressure moved progressively towards the head, so towards the top of the manipulandum. In upside-down posture, load force was higher for collisions towards feet leading to the displacement of centers-of-pressure in this direction, thus towards the manipulandum bottom during the task. Regarding the supine posture, while centers-of-pressure did not evolve for the thumb, the index finger moved across collisions towards the manipulandum's bottom. This could seem surprising because gravity had the same influence on both fingers. Nonetheless, fingers were quite misaligned at the block beginning. The index displacement allowed a realignment to take place. Actually, whichever their orientation, subjects readjusted their fingers positions, tending to align them. In the right-side-up posture, this misalignment was already small at the beginning of the task, whereas it was quite larger before performing collisions in supine or upside-down orientation. Its decrease was thus smaller in the right-side posture than in the two other postures. This misalignment was also observed in the upside-down posture during arm oscillations by Opsomer et al. in 2021 [15]. The realignment of fingers is important since a large misalignment of the fingers means that the load force on each finger will be unequally distributed. But when this misalignment decreases, load force is then more evenly distributed on fingers.

4.2.2 Grip force

We will here focus on grip force at contact. Although slippage risk is arguably influenced by contact velocity, which was detailed in the section about kinematics (see section 4.1), the first parameter to take into account is the load force experienced by the fingers on the contact surface. And in order to avoid slippage, participants have control on the contact grip force they apply, in addition to the contact velocity. Grip force at contact is a noteworthy parameter since we are mostly interested in the predictive mechanisms subjects put in place during collisions. Grip force maximum is probably also programmed in advance [18] but it is potentially influenced by sensory feedback. Note that it was similar to $\text{GF}_{contact}$ which was smaller within 3 N.

Grip force is impacted by subjects' posture

Regarding the right-side-up position, since grip force is linked to load force according to Equation 2, we noticed that it was also higher for movement towards the head than for feetward movements. This indicates that the directional dependencies of load force were anticipated by the participants. It is consistent with results found by White et al. (2011, 2012) [17, 18]. Note that in the case of headward collisions in our experiments, subjects already gripped the manipulandum harder at movement onset relative to feetward collisions.

By the same token, when being upside-down, load force towards the feet was greater than towards the head. Similar behavior was observed for grip force confirming that it followed load force and thus supporting our assumption of an allocentric reference frame in the upside-down orientation. Humans fine-tuned grip force based on an internal model allowing a load force estimation that was quite accurate when they were upside-down.

Regarding the supine posture, load and grip forces behavior differed whether subjects opened or closed their eyes. But in both cases, grip force was following load force. With eyes open, both LF_{max} and $\mathrm{GF}_{contact}$ did not statistically differ between headward and feetward collisions while with eyes closed, both load and grip forces were larger for headward collisions versus feetward collisions. Grip force was thus well adjusted to load force.

In the two unusual postures, our results showed that contact grip force was decreasing across blocks. We stated two hypotheses explaining that. Either subjects were more and more used to performing the task in these positions and developed an internal representation of load force that was more and more accurate, they could thus afford a smaller grip force after having performed the task a certain number of times. Or maybe they were more and more tired of performing such an unusual task and thus gripped less harder the manipulandum during the last blocks.

Moreover, since load force values across the three postures varied within the same range, it could be expected that values of grip force at contact would also be similar whichever the posture. However, while grip force was not significantly different between right-side-up and supine orientations, it was significantly higher when subjects were upside-down. This was also observed from an allocentric viewpoint. Even if for skyward collisions, LF_{max} was not significantly different whether collisions were performed right-side-up or upside-down, $\mathrm{GF}_{contact}$ was larger when subjects were upside-down. The same went for groundward collisions. And actually, upside-down grip force was already greater than right-side-up and supine gripe forces at the movement onset. It shows that from the outset, subjects gripped the manipulandum harder in this unusual position. It is consistent with the work of Opsomer et al. (2021), with weightlessness experiments of Crevecoeur et al. (2010) and with parabolic flight experiments of Augurelle et al. (2003) and Crevecoeur et al. (2009) [1, 5, 6, 15]. Subjects felt less comfortable when being upside-down, explaining why they applied a larger grip force than they should. It was reported that this higher grip force is a consequence of humans' uncertainty about load force in uncommon environments [5, 9]. This result highlights the particularity of the upside-down environment and can also be explained by the safety margin. As a matter of fact, this safety margin was greater when participants were upside-down than when they were supine (see Figure 31 in Appendices). It was also larger than in the right-side-up posture, but not significantly. Our results about safety margin will be discussed more extensively later on.

Grip force is impacted by subjects' vision condition

Regarding the eye conditions, grip force we measured was on average higher when subjects closed their eyes, as it was the case for load force. More precisely, on the one hand, LF$_{max}$ of feetward collisions was similar for both vision conditions, and GF$_{contact}$ followed a similar pattern. On the other hand, headward collisions were performed with higher LF$_{max}$ when participants closed their eyes than when they opened them. And the grip force at contact was also adjusted accordingly. Contact grip force was thus well adapted to load force maximum regarding the vision condition.

Vision is of greater importance when subjects are supine

Grip force when subjects were supine can be analyzed separately, whether they had eyes open or closed. One can notice that in the first vision condition, GF$_{contact}$ was not statistically different between headward and feetward collisions. This leads us to believe that in the supine orientation with eyes open, grip force was programmed in an Earth-centered reference frame. Indeed, in this position, gravity made the same contribution to headward and feetward collisions. But when subjects closed their eyes, then headward grip force was greater than feetward grip force. White and colleagues (2012) had the same results in microgravity at impact time. As a matter of fact, they showed that in novel environments such as 0g, subjects applied larger grip force at contact in the case of headward versus feetward collisions. Note however that during White and colleagues' experiments, subjects had eyes open while we observed similar results in our experiments when subjects closed their eyes [17]. This leads us to conclude that when being supine with eyes closed, grip force planning switch to a body-centered reference frame. Furthermore, whether for headward or feetward collisions, GF$_{contact}$ was similar between the right-side-up and the supine posture. However, in the case of headward collisions, LF$_{max}$ was slightly different between these two conditions but not statistically and for feetward collisions, it was significantly different. This supports a control in an egocentric reference frame when subjects closed their eyes when being supine.

In brief, regarding the supine orientation, having eyes open allowed for greater assessment of body orientation with respect to gravity, leading to an allocentric referential frame. But when participants did not have vision anymore, the referential frame tends to be egocentric since they were less aware of the surroundings.

Actually, these dependencies of the reference frame on both vision condition and subjects' orientation are due to a movement planning based on multimodal cue information. As already proposed by, among others, Le Seac'h et al. (2007), a multimodal reference frame is used when planning arm movements [13]. Indeed, motor control is based on an integration of several sensory systems, namely the somatosensory, the visual and the vestibular ones. Movements performed during our experiments in right-side-up and upside-down postures were parallel to gravity whereas in the case of collisions performed when being supine, they were perpendicular to gravity. In this later condition, since the gravitational vector was perpendicular to the body axis, the vestibular system became less reliable to perceive gravity orientation [7, 13, 19]. Motor control was then more based on somatosensory and visual cues in this position. Thus, one hypothesis could be that the effect of gravity is more prominent in right-side-up and upside-down than in supine orientation. Gravitational signals may override visual cues in these two subjects' postures, but not in the supine one. Consequently, this substantiate that the weights of sensory systems are adjusted according to the condition in which subjects are. Depending on how this sensory information is weighted, the reference frame is different.

All in all, our observations are globally consistent with our assumptions. Grip force was indeed greater for headward than feetward collisions in the right-side-up orientation, and greater for feetward than headward collisions in the upside-down orientation. Concerning the different positions, while the reference frame seems to be allocentric in the upside-down posture, it seems to be influenced by vision in the supine orientation. When considering eye conditions, there were indeed differences whether subjects performed collisions with eyes open or closed. But eye condition alone does not appear to totally impact the reference frame, which also depends on the subject's orientation. Both posture and vision condition seem to be relevant and should be taken into account when studying the reference frame, especially in the supine posture. This is in line with the hypothesis of a multimodal reference frame.

Grip force maximum occurs after contact

Various authors reported that grip force peaked after the impact time [3, 17, 18]. In our experiments, this grip force peak was occurring approximately 75 ms after contact, which is in the same range as the 65 ms reported by White and colleagues (2011). These authors suggested that the maximum grip force value and its time occurrence could reflect an adaptation depending on the task performed [18]. In our results, grip force maximum occurred later when subjects performed feetward than headward collisions. What is more, at contact time, their velocity was larger in the case of feetward than headward collisions. We hypothesize that participants may feel, unconsciously or not, that it was more important to increase the damping at contact in these feetward collisions where contact velocity was larger. Indeed, having a less stiff contact between manipulandum and hand allows to quickly damp a large proportion of the destabilizing vibrations. Consequently, subjects maybe gave more importance to damping than to a safer object stability for feetward versus headward collisions.

The value of the grip force peak did not seem to be largely influenced by the time at which it was reached, even if it tended slightly to decrease when this time increased. Indeed, grip force control relies mostly on a predictive component, in addition to a reactive component of lesser importance.

4.2.3 Safety margin

As a reminder, the safety margin is the difference between the normal force exerted on the manipulandum and the slip force, divided by this slip force. A positive safety margin allows to mitigate slippage risk. Some authors have shown that safety margin should be proportional to the uncertainty about the impact, because then, a larger range of load force can be expected [9, 17].

As already explained, safety margin depends on the finger coefficient of friction, which is influenced by skin moisture. It is important to note that between some blocks, some subjects were wiping their hands since they felt they were moist. The measure of the coefficient of friction after the eight blocks in one condition is thus maybe mildly altered, and its value might be somewhat underestimated.

Safety margin evolution in right-side-up posture

Regarding safety margin in right-side-up orientation, it is logical that we did not observe adaptation along blocks since subjects are used to this position and they already put in place a proper strategy to deal with gravity and the risks of dropping an object. Opsomer and collaborators (2021) found the same result for oscillatory movements.

For headward movements, our observations are consistent with the fact the grip force at contact remained stable along blocks in this condition. It is as if participants estimated that the grip force level they applied during the first block was sufficient in order to prevent the manipulandum from falling out of their hand and should not be increased.

But interestingly, we reported that for feetward collisions, $\text{GF}_{contact}$ was decreasing. Firstly, we consider the case where subjects had their eyes open for feetward collisions. On the one hand, slip force was decreasing along blocks. This should result in an increasing safety margin. On the other hand, contact grip force was also decreasing along blocks, which should lead to a decreasing safety margin. It is possible that these two effects counteract each other, resulting in a stable safety margin along the four blocks. Secondly, in the eyes closed condition, the fact that both safety margin and slip force were stable along blocks while the grip force at contact was decreasing can perhaps be partly explained by the friction coefficient, which is also influencing safety margin. As a matter of fact, the larger this friction coefficient, the smaller the normal force that must be applied on the manipulandum. And for feetward collisions in right-side-up position, the friction coefficient was slightly larger after the eight right-side-up blocks than before (while it was not the case for headward collisions). This have resulted in a smaller slip force, thus a larger safety margin at the last block than at the first one. So on the one hand, $\mathrm{GF}_{contact}$ was decreasing across blocks but on the other hand, the static friction coefficient was increasing, explaining that the safety margin stayed stable along the blocks for feetward collisions with eyes closed in right-side-up posture.

Safety margin evolution in supine posture

Concerning our results in supine posture, the safety margin when subjects had eyes open and for feetward movements with eyes closed was decreasing across blocks, as it was the case of $\mathrm{GF}_{contact}$ while the load force maximum (and the slip force) was stable between the four blocks. In this case, it was thus the grip force adaptation that conditioned the safety margin adjustment since it was decreasing across blocks while slip force stayed stable. Likewise, Augurelle et al. (2003) reported a similar safety margin adaptation in weightlessness [1]. Nonetheless, when participants closed their eyes and performed headward movements, they did not adapt their safety margin along blocks, while their grip force at contact evolved. But this grip force was less decreasing than in the three other cases. This may explain the stable safety margin in this condition.

Safety margin evolution in upside-down posture

If we now look at safety margin evolution when subjects were performing headward and feetward collisions upside-down, there were two distinct behaviors depending on the vision condition.

Firstly, when subjects opened eyes, safety margin was decreasing across blocks. Indeed, participants applied a lower $\mathrm{GF}_{contact}$ at the fourth block than at the first one while slip force was stable. Our explanation is that after these four blocks with eyes open, they already experienced this position and were more able to modulate their safety margin accordingly. The fact that safety margin decreased across blocks may reflects that subjects became more and more confident about the grip force they must exert with time. A similar safety margin strategy has been observed for oscillations in an upside-down posture with Opsomer and his colleagues (2021) [15].

Secondly, when they closed their eyes in this unusual posture and performed feetward collisions, they adopted the same behavior as the one just explained. Indeed, while $\mathrm{GF}_{contact}$ decreased along blocks, slip force stayed constant for this specific condition. However, it is only for headward collisions with eyes closed that subjects were observed to adopt another strategy by keeping a stable safety margin along blocks while $\mathrm{GF}_{contact}$ was decreasing along blocks. Subjects had apparently not a total growing confidence in this new posture when they had eyes closed, while it appears to be the case when they had eyes open since safety margin was then decreasing.

As a consequence, we can say that in supine and upside-down postures, the safety margin adaptation during collisions performed with eyes open was accurate. The safety margin decrease is a strong indicator of subjects' growing confidence in these two positions. But when participants closed their eyes, this adaptation was incomplete. A proper adaptation with eyes closed in these unfamiliar conditions probably requires more blocks. Complementary studies could further investigate the differences in safety margin adaptation between eyes open and closed condition in these supine and upside-down orientations.

Allocentric comparison

Concerning the comparison of safety margin in an allocentric reference frame, at first sight, it could seem reasonable to expect a larger safety margin for collisions pointing towards the sky, since they were performed against gravity and thus more prone to slippage. Yet, this is not what we observed in Figures 27 and 28. This is explained by a larger slip force in the case of skyward collisions versus collisions oriented towards the ground. Indeed, in our results, the maximum of load force was larger for collisions performed against gravity than following gravity. And it can be observed in Equation 6 that the higher the slip force, the lower the safety margin.

Additionally, safety margin was not affected by collision direction when participants were supine. This result seems coherent since gravity played the same role for headward and feetward movements in this position. Consequently, the risk of slippage was the same whichever the movement direction.

Effect of subjects' vision condition on safety margin

Regarding movements going against gravity, surprising as it may seem, we did not report any effect of vision. We suggest that the safety margin control could be a combination of both the learning and vision condition. As a reminder, subjects alternated blocks between eyes open and closed condition. The first block with eyes closed was thus the second block, where subjects had less visual information compared with the first one. Thus, safety margin was expected to be larger since subjects were more uncertain about collisions. But they already made one block of collisions in the same position so they were familiar with the task. Consequently, the safety margin should be smaller than in the previous block. These two effects could counterbalance each other, explaining why subjects applied a similar safety margin as in the previous block with eyes open.

Concerning movements performed following gravity, feetward movements in right-side-up posture exhibited a larger safety margin in the closed compared with the eyes open condition. Indeed, the uncertainty about collisions is doubtlessly larger when subjects are deprived of their sight, explaining why subjects tended to grip harder than they should in this familiar position with eyes closed. Strikingly, the inverse phenomenon was observed in the upside-down posture. But in this case, slip force was higher when subjects closed their eyes regarding the eyes open condition, while grip force was not statistically different. Indeed, it was observed in section 3.5 that the maximum of load force of upside-down collisions was smaller when subjects opened versus when they closed their eyes whereas $\mathrm{GF}_{contact}$ was not affected by vision in this condition. This tended to increase the safety margin value in the eyes open condition when subjects were upside-down. Note that for feetward collisions in the right-side-up condition, slip force and load force were of similar values when comparing open and closed vision conditions. Slip force does thus not impact safety margin comparison between eyes open and closed condition in this specific case.

Furthermore, since safety margin should be proportional to the uncertainty about the impact, we were expecting to have a larger safety margin when subjects closed their eyes in supine position, because it was then more difficult to predict the collision. Thus, it may be a good strategy to cope with higher risks of dropping the object. Nevertheless, it is not what we observed. The safety margin was similar in both vision conditions when subjects were supine. The visual information did not seem important in this case. It is as if the first block performed with eyes open was sufficient to memorize the impact.

Negative safety margin does not necessarily means that the object dropped

Another interesting result is that when being supine and in the case of headward collisions performed right-side-up, the safety margin was negative. Actually, when looking at the safety margin computed with the normal force at time of maximal slip force, it was only the case for feetward collisions in the supine posture. Maybe that in this particular condition, impact was not well predicted. But we would be surprised that impact in supine posture was less efficiently anticipated than when being upside-down. We rather think that subjects were confident and felt they could afford a small slippage, since the normal force they exerted was smaller than the minimal normal force required to avoid slippage. Indeed, during collisions, there is often slippage. But it is not straightforward to interpret since the impact is very short and the slip is thus due to an impulse force.

4.3 How dynamics and kinematics are related?

At the impact time, Equation 1 linking load force to acceleration changes. Indeed, there is then also a reaction force of the target, F_r, to take into account. This term is related to the impact itself. It is influenced among others by the target stiffness and deforms its foam. Furthermore, target deformation also depends on load force. The equation at impact then becomes:

$$\overrightarrow{LF} + \overrightarrow{F_r} = m \cdot (\overrightarrow{a} - \overrightarrow{g}) \tag{7}$$

At this time, the force is distributed between LF and F_r. However, we do not know how. The presence of F_r means that we cannot quantify load force by knowing only the mass, acceleration and gravity. This reaction force is the reason why the link between contact velocity and load force maximum is not trivial. At first glance, one might think that since contact velocity is an indication of how much energy has to be absorbed, it should be proportional to load force maximum. But it is not the case. If load force was null, all kinetic energy at impact time would be converted in potential energy, reflected by the foam deformation. Reaction force would thus be proportional to contact velocity. But since load force was not null, this external force has to be taken into account. The relation between load force and contact velocity is thereby not straightforward. It is therefore more likely that the sum of load force and reaction force is proportional to contact velocity rather than load force alone.

Moreover, the accuracy of load force maximum values is questionable. The compression phase during which the manipulandum is in contact with the target is quite complex, and extremely short. We do not know to which extend the peak LF values measured by the sensors during our experiments are representative of the real values.

These reasons are arguably explaining why maximum load force and velocity, which is the integral of the acceleration, did not exhibit the same behavior across the three different participants' orientations.

For further research projects, it could be interesting to place force sensors within targets to quantify this reaction force and have an idea of how the total force is distributed between the load force and the reaction force during collisions.

4.4 Multimodal reference frame for arm movement planning

Our results suggest that grip force dynamics seem to be globally planned in an Earth-centered reference frame while kinematics are planned in a body-centered reference frame. Likewise, Opsomer and his colleagues (2021) observed that for oscillatory movements in right-side-up and upside-down postures, grip force dynamics were planned allocentrically whereas kinematics were planned egocentrically. They also reported that kinematics adaptation to the upside-down posture was slower than grip dynamics adaptation [15]. In our results, one can also observe that dynamics adapted quite rapidly to novel gravitational environment, while kinematics did not evolve considerably along the eight blocks. We discussed in section 4.1.3 three possible hypotheses explaining the lack of velocity adaptation. Firstly, the predominance of the alignment of headward and skyward direction in daily life. Secondly, the hypothetical incomplete sensory signals that could be not representative enough of the real fall risk of the object. Thirdly, the fact that kinematics required maybe more time in order to adapt itself to a new environment. This last assumption seems to be the most reasonable. The two first ones would be less consistent with the fact that grip force behavior was globally well adapted to subjects' orientations. But even if it would be surprising that dynamics showed a rapid adaptation to novel environment without reliable sensory information and despite a preponderant idea of our head pointing skywards, perhaps dynamics and kinematics do not give the same weight to the same input signals. All this is in agreement with the conclusion of Opsomer et al. (2021) about distinct mechanisms behind grip force dynamics and arm kinematics adaptation in unfamiliar gravity environments [15].

As already discussed, when subjects were supine, grip force appeared to be planned allocentrically when they had eyes open and egocentrically when they had eyes closed. The reference frame in which dynamics about collisions are planned seems to change from one condition to another, and does not seem to be strictly allocentric or egocentric. It appears to depend on both subjects' position and vision. Motor planning relies thus on multimodal signals. The internal model uses multisensory information in order to optimize hand movement. However, this statement is based on observations we made about grip force. Indeed, kinematics seem to be planned egocentrically, whichever the condition. Nonetheless, we noticed a subtlety about time-to-peak-velocity. When subjects were supine, we reported that headward TPV arose before feetward TPV when they closed their eyes, but not when they opened them. Le Seac'h and his colleagues published similar results in 2007 in their paper about discrete movements. Time-to-peak-velocity behavior of subjects in the supine orientation is in agreement with movement planning based on multimodal information, as it was affected by both subjects' position and vision [13]. Thereby, although it is our dynamics results that highlight a multimodal reference frame, this seems to also apply to kinematics, but to a lesser extent in our case.

To study further this multimodal reference frame, it could be interesting to know whether the observed differences between right-side-up and supine positions are due to the subjects' orientation or to gravity. In our experiments, we studied head-feet collisions. It could be noteworthy to also study collisions that are perpendicular to these head-feet collisions. We could imagine an experiment where participants perform both parallel and perpendicular collisions with respect to gravity in a right-side-up and a supine orientation. When being right-side-up, gravity would impact vertical collisions towards head and feet but not horizontal collisions to the left and right. When being supine, gravity would have no effect on head-feet collisions while it would impact collisions performed skywards and groundwards. By doing so, we could distinguish the influence of body axis from the gravity effect. Similar experiments were done with discrete movements in 2007 by Le Seac'h and colleagues [13].

5 Conclusion

To conclude, the results presented in this study demonstrate a quite suitable adjustment of grip force when performing collisions. Our work allows to emphasize the predictive behavior of grip force and its adaptation to novel environments, taking place thanks to a flexible internal model integrating a gravity assessment.

Our experiments confirm that grip force is greater for headward collisions compared with feetward collisions in the right-side-up posture. Regarding the different orientations, while this force seems to be controlled in an allocentric reference frame when being upside-down, it is less straightforward when it comes to the supine posture. Actually, we suggest that collisions are planned based on a multimodal reference frame. In addition to being influenced by subjects' position, the movement planning is also influenced by vision. When participants open their eyes, they tend to take into account their body orientation in relation to gravity, relying on an allocentric reference frame, whichever their orientation. But when they are supine, since collisions are perpendicular to gravity, the absence of vision could decrease the weight of body orientation in the multisensory cue combination, leading to an egocentric reference frame. In contrast, gravitational signals seem to be of larger importance when participants' orientation is aligned with gravity, so when they are right-side-up or upside-down.

Dynamics and kinematics involved in myriad daily manipulations implicating collisions of an object with its surroundings appear to rely on a multimodal reference frame. Even if grip force dynamics exhibited an adaptation along blocks, it was not the case for arm kinematics, which seemed to stay preferentially planned egocentrically. Arm dynamics and kinematics adaptation to unfamiliar gravity environments would thus rely on distinct mechanisms. Therefore, further research is required to discern if longer exposure to a novel gravity environment will allow a kinematics adaptation and to investigate more deeply these distinct processes underlying dynamics and kinematics during controlled collisions tasks.

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6 Appendices

6.1 Time between impact and maximum load force

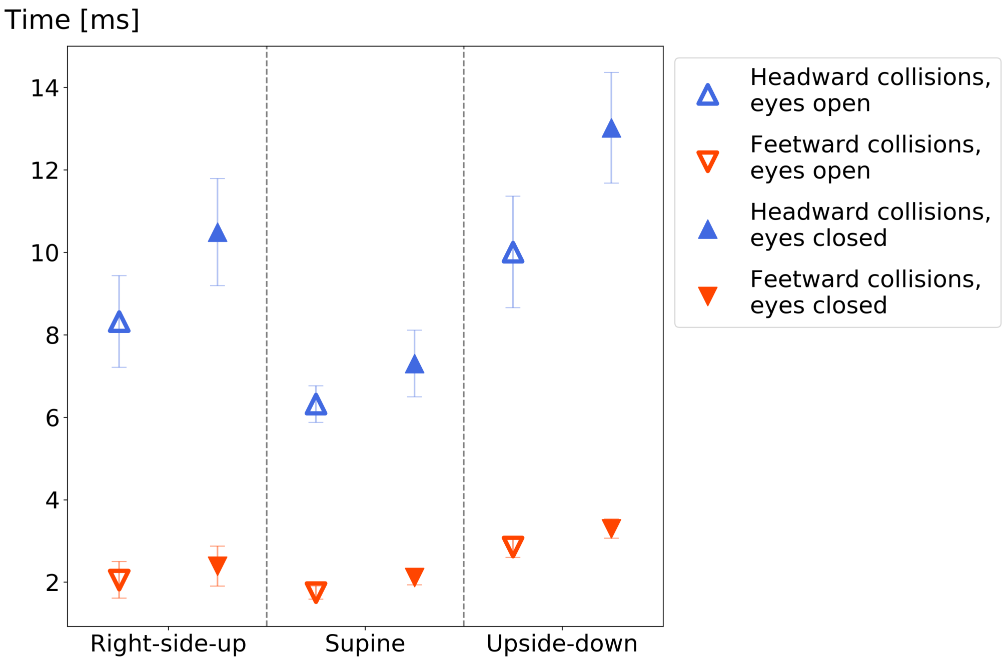

Figure 29: Mean of the time between impact and maximum load force for headward and feetward collisions in all conditions across all subjects (n = 18). The headward and feetward collisions are separated and illustrated by blue and red triangles respectively. The eyes open and closed conditions are illustrated by empty and solid triangles respectively. Error bars represent standard error.

6.2 Grip force at movement onset

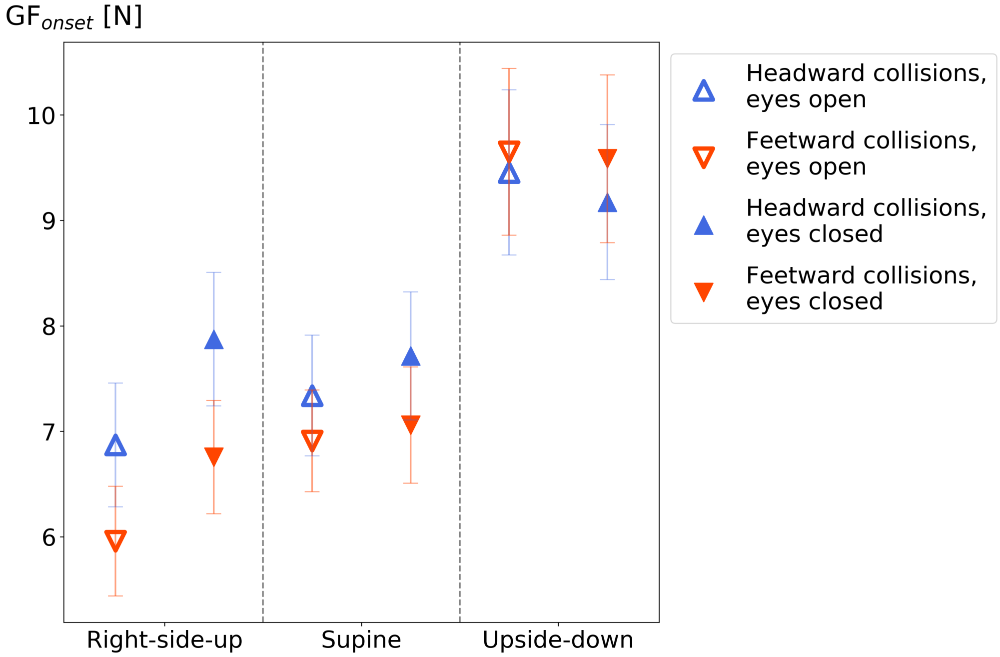

Figure 30: Grip force at movement onset (GF$_{onset}$) means for headward and feetward collisions in all conditions across all subjects (n = 18). The headward and feetward collisions are separated and illustrated by blue and red triangles respectively. The eyes open and closed conditions are illustrated by empty and solid triangles respectively. Error bars represent standard error.

6.3 Safety margin evolution

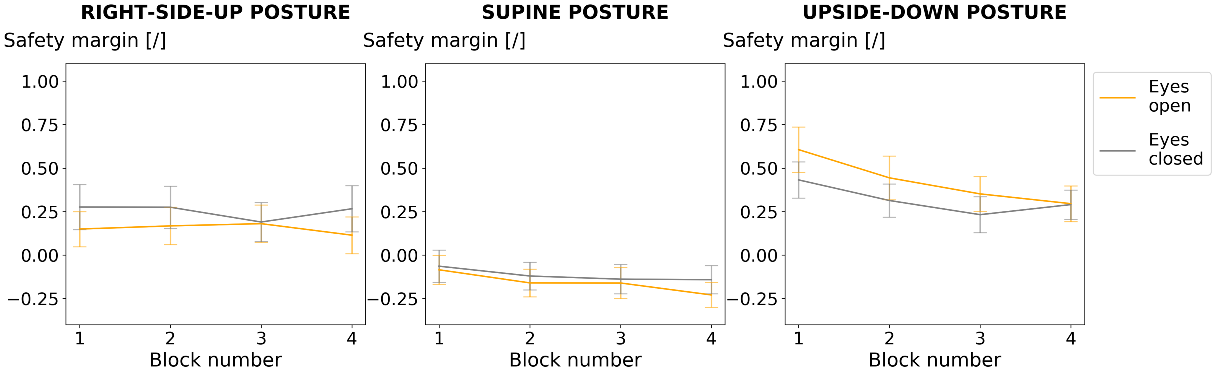

Figure 31: Evolution of safety margin means in right-side-up (left panel), supine (middle panel) and upside-down (right panel) postures in the four blocks across all subjects (n = 18). The eyes open and closed conditions are separated and illustrated by orange and gray curves respectively. Error bars represent standard error.

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