

École polytechnique de Louvain

Investigation of a haptic illusion created by gravity

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Abstract

This master thesis investigates the impact of gravity on haptic illusions, building on previous research that identified a perceptual illusion where upward forces (against gravity) are perceived as larger than downward forces (with gravity). Investigating this illusion is crucial for improving human-machine interfaces in aerospace and medical fields. An experimental study with 15 participants was conducted to explore these effects. Participants performed two tasks: creating friction on a manipulandum to analyse the coefficient of friction and executing isometric forces. These tasks were carried out under four conditions, defined by combinations of body orientation (seated or supine) and force direction (vertical or horizontal). These combinations allowed the observation of the forces when the axis of gravity relative to the body and the direction of the forces varied. The aim was to understand how changes in body orientation and force direction influence the perception of exerted forces, providing insights into the underlying mechanisms of haptic illusions.

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Chapter 1

Introduction

In physics, gravity is one of the four fundamental interactions in the universe, alongside electromagnetism and the strong and weak nuclear forces. Coming from Latin *gravitas* meaning 'weight' [1], it is a "fundamental interaction which causes mutual attraction between all things that have mass".[2] The formula of the law of universal gravitation is given in Figure 1.1.

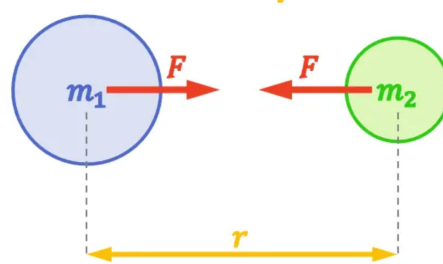
$$F = G \frac{m_1 \cdot m_2}{r^2}$$


Figure 1.1: Law of universal gravitation [3]

As we can see, the force caused by gravity depends on the mass of the bodies and the distance between their centers. The Moon's mass is equivalent to 1.23% of the Earth's. The Moon's gravity is thus approximately 1/6th that of Earth's. In celestial bodies like Earth and the Moon, there are regions where mass is unusually dense, known as mass concentrations or mascons. These can cause local variations in gravity. For example, the Moon has several mascons, which were first detected by the variations they caused in the orbits of spacecraft. [4][5]

During space missions, astronauts are subject to changes in gravity. It is therefore important to understand the changes that occur in the body when gravity varies, in order to better understand the challenges and the design of the machines used during these missions.

The term "haptic" refers to anything related to the sense of touch and the perception of objects through tactile sensations. A study [6] conducted by Laurent Opsomer and colleagues has discovered that a haptic illusion that upward forces are larger than downward forces is created by gravity. This illusion is considered by the authors to be an overesti-

mation of upward forces and/or an underestimation of downward forces. It disappears in microgravity and is increased in hypergravity.

This master thesis is therefore set in this context and investigates this haptic illusion created by gravity. The manuscript will be divided into several parts. Firstly, a state of the art will be drawn up in order to understand the various elements inherent in the study that led to the determination of this master thesis topic. It will present the impact of gravity on object manipulation, the importance of haptic feedback in order to understand how the haptic illusion discovered can have an impact on our lives, the sense of orientation and its interest in the study being carried out and finally what happens in our body when gravity varies, including a deeper presentation of the study of Laurent Opsomer and colleagues. The experiment's equipment and methods will then be detailed. The various results will be presented, followed by a discussion and suggestions for further studies. Finally, the thesis will conclude with a summary of findings.

Chapter 2

State of the art

2.1 Impact of gravity on object manipulation

As it has been discovered that a haptic illusion exists when manipulating objects in a gravity or hypergravity environment, it is important to find out about the impact of gravity when manipulating objects in order to be able to understand the mechanisms involved in the study that led to this discovery.

Throughout our existence, we have been constantly exposed to the Earth's gravity, shaping the way we learn and execute all forms of movement under its influence. Although not perceptibly felt, gravity serves as an axis of reference that significantly influences the planning and execution of our movements at different levels.

Gravity impacts the prediction of movement outcomes, such as limb acceleration or postural imbalances, requiring the central nervous system (CNS) to anticipate and compensate for these effects to maintain balance and movement efficiency. This anticipatory assessment is therefore essential for adjusting the force, direction and duration of motor commands before movement is initiated.

Moreover, there is a time lag between the moment when a motor decision is made (signal sent by the brain) and the moment when the movement is actually performed by the muscles. Predicting the consequences of motor commands helps to compensate for these delays, ensuring that movements are executed smoothly and precisely.

Additionally, when performing movements that cause a shift in the center of gravity, such as bending or jumping, preemptive postural adjustments are imperative for equilibrium maintenance. This anticipation helps prevent falls and ensure a smooth transition from one posture to another. [7]

2.1.1 Internal models

Internal models are neural mechanisms capable of simulating the dynamics of body limbs and environmental objects, thus allowing the prediction of future states. The article [8] discusses with internal models, in particular **inverse models** that calculate the motor commands required to achieve the desired trajectory (movement planning), and **forward models** that predict the sensory consequences of motor commands and compensate for sensorimotor delays. The article [9] also investigated the interest of internal models in the production of adaptive behaviour. This includes the management of sensory feed-

back and motor planning in order to correct disturbances and achieve the desired motor outcomes efficiently. These internal models are represented on the Figure 2.1.

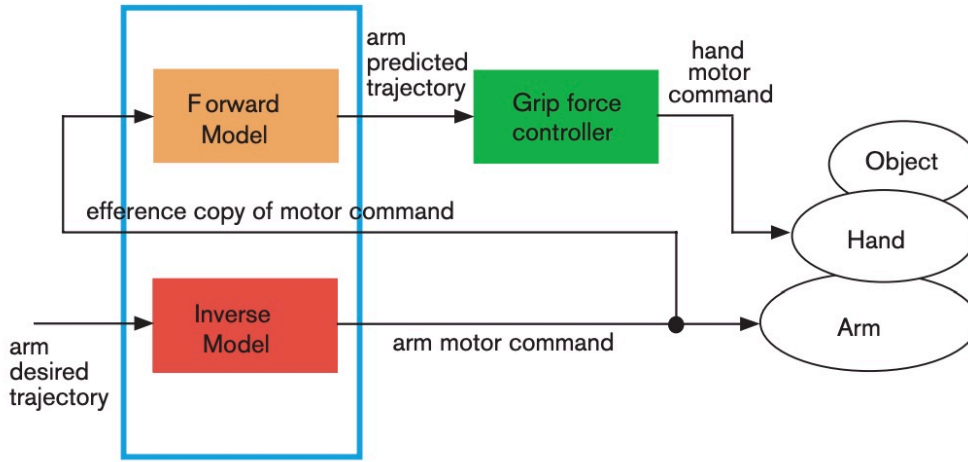


Figure 2.1: Internal models [8]

It emphasizes the inadequacy of feedback control alone for fast and coordinated arm movements due to slow biological feedback loops, proposing that the brain acquires an inverse dynamics model of the object to be controlled for effective motor control in a feedforward manner.[10]

Efference copies play a vital role in the perception of effort and potential haptic illusions. They are replicas of motor commands sent to the muscles, used by the brain to predict the consequences of movements. This mechanism helps distinguish between self-generated sensations and those caused by external stimuli, which is essential for precise motor control and a coherent perception of the environment. [11]

The sense of effort is the conscious perception of the muscular effort required to perform an action. This perception is influenced by efference copies, which inform the brain about the anticipated effort for a given movement. Nevertheless, gravity inherently biases muscular effort: exerting a given force downward in the direction of gravity demands less effort than exerting the same force upward against gravity. Thus, if muscular effort contributes to force estimation, this difference in required effort can lead to haptic illusion of the applied forces, especially under the influence of muscular fatigue. [6] [12]

To fully understand the effect of gravity, it is important to explain the difference between the sense of effort and the sense of forces, and how the sense of effort can contaminate the sense of forces. The sense of forces is the perception of the actual force applied or felt, independent of muscular effort. The sense of effort, on the other hand, is the perception of the amount of muscular effort required to produce a force. When additional effort is needed to overcome gravity, the sense of effort can "pollute" or bias the sense of forces, making it seem like a greater force is being applied when it is simply the increased effort due to gravity.

Thus, the perception of muscular effort (sense of effort) can interfere with the accurate perception of the forces applied (sense of forces), especially in conditions where gravity plays a significant role or when the muscles are fatigued. This distinction is crucial to understanding how and why haptic illusions may occur.

In the context of object manipulation, it is imperative that the internal models incorporate a comprehensive understanding of the mechanical properties of both the arm and the object. This includes an accurate assessment of the arm's mass, inertia and stiffness, as well as the object's mass and friction coefficient, for example. In addition, an accurate estimate of the direction of gravity is crucial as it directly affects the perceived weight of the object. Errors in the perception of the direction of gravity and of the weight of the object can lead to an incorrect estimate of the force required to manipulate the object, leading to haptic illusions where the force actually applied and the perceived force diverge.

The paper [13] also highlighted the internal representation of the interaction between the arm and the dynamics of the environment during the generation of arm trajectories, indicating that gravity is a crucial factor taken into account by the brain in motor planning and execution. Thus, this complex interplay of factors is essential for accurately predicting and executing manipulative actions.

2.1.2 Coordination of grip force and load force

The two main forces that govern the grasping of an object :

- The *grip force* (GF) is the normal force to the surface of an object held in precision grip (between the thumb and the index finger).
- The *load force* (LF) is the tangential force at the surface of the object and can be written as :

$$\vec{LF} = \textcolor{red}{m}\vec{a} - \textcolor{blue}{m}\vec{g} \quad (2.1)$$

with $\bullet = \textcolor{red}{\bullet}$ = inertial part and $\bullet = \textcolor{blue}{\bullet}$ = gravitational part.

These two forces are showed in Figure 2.2.

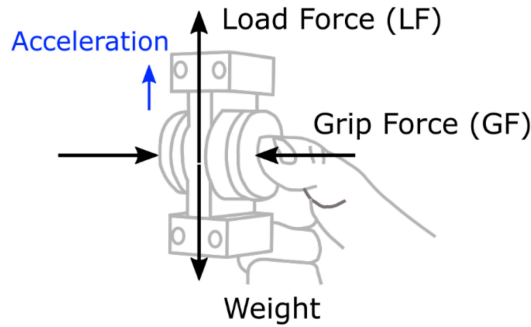


Figure 2.2: Grip and load forces [14]

They enable the precision grip to pick up an object, move it and manipulate it according to a very specific task.[7]

However, they must be carefully controlled to avoid slippage while minimising muscle fatigue. The grip force GF can be used to determine the maximum friction force $F_{f_{max}}$ that can be applied without slipping. Indeed, this $F_{f_{max}}$ is proportional to the grip force (GF) and the static friction coefficient (μ). By definition, this force is expressed as :

$$F_{f_{max}} = \mu \cdot GF. \quad (2.2)$$

If LF is parallel to the contact surfaces, it is purely a frictional force.

Thus, if the forces are distributed symmetrically between the thumb and the forefinger, it can be written that :

$$\frac{LF}{2} \leq F_{f_{max}} \quad (2.3)$$

and then :

$$GF \geq \frac{LF}{2\mu}. \quad (2.4)$$

This means that the grip force must be large enough in proportion to the load force so that the object does not slip. This leads to the fact that grip force and load force must always be coordinated.

This synchronisation was observed in 1984 in the study described in paper [15]. It delves into the intricacies of how humans manage to lift and hold objects with precision. The Figure 2.3 shows the general structure of a lifting and holding trial. The coordination of the Grip force and the Load force over time was analysed through the ratio between them and can be seen on the bottom trace in the figure. As said before, to prevent slips, this ratio need to be larger than the slip ratio that is determined, due to 2.4, as $slip\ ratio = \frac{1}{2\mu}$.

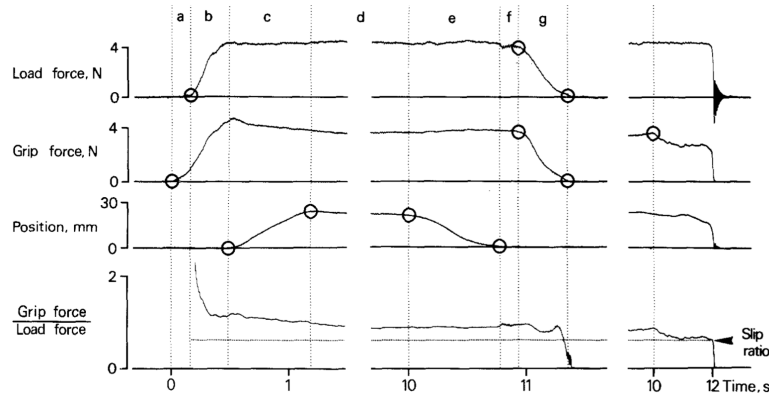


Figure 2.3: Lifting and holding objects with different surface textures [15]

Later, other research such as [16] has shown that even when the LF varies due to the inertia of the object during upward and downward movements, the GF is finely modulated by these changes as it can be seen on Figure 2.4.

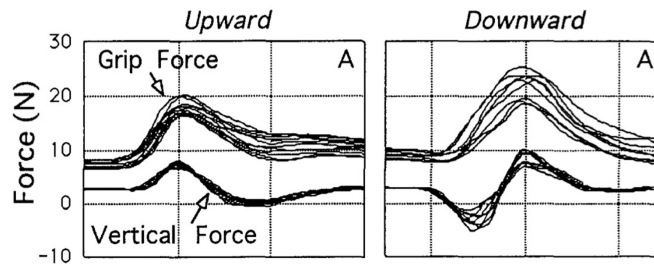


Figure 2.4: Coordination of GF and LF during upward and downward movements [16]

These evolutions can be seen on the phase diagram on the Figure 2.5 that represents rhythmic movements.

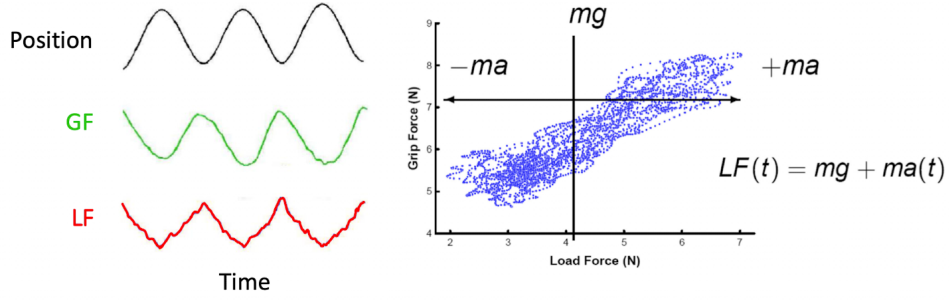


Figure 2.5: Phase diagram of GF and LF (absolute value) [7]

2.2 Importance of haptic feedback

In physiology, haptic feedback refers to the sensory feedback that an individual receives through touch and physical interaction with their environment. In a broader sense, it also includes proprioceptive feedback from the muscles of the hand and arm, and its potential impact on the illusion created is described in more detail in section 1.4.3.

Haptic feedback encompasses a range of sensations, including pressure, vibration, texture and temperature, which are detected by various types of mechanoreceptors in the skin, also called tactile receptors. In the case of this master's thesis, what is important are the mechanoreceptors found in the glabrous skin that can be seen on Figure 2.6 :

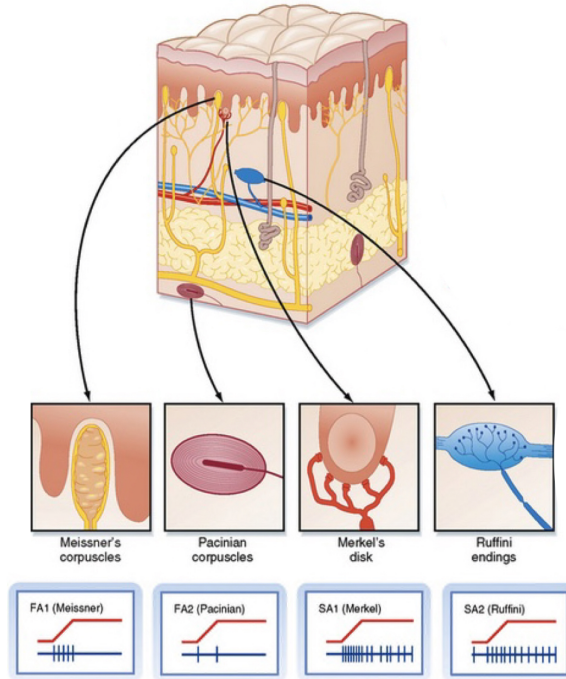


Figure 2.6: Mechanoreceptors [17]

- Meissner corpuscles : sensitive to light touch
- Pacinian corpuscles : sensitive to vibration
- Merkel disks : sensitive to pressure
- Ruffini endings : sensitive to skin stretch.[18]

Tactile afferents, that innervate the inside of the hand, are fast-conducting myelinated afferent neurons that convey signals from the mechanoreceptors to the brain. They signal the transformation of soft tissues that occurs when the hand interacts with objects, thereby providing information about the contact between the hand and the object, as well as the physical properties of the object. The human hand has four functionally distinct types of tactile afferents that can be seen on the bottom on Figure 2.6 :

- FA-I (fast-adapting type I) in Meissner corpuscles : exhibit sensitivity to dynamic skin deformations of relatively high frequency
- FA-II (slow-adapting type II) in Pacinian corpuscles : excited when hand-held objects contact or break contact with other objects
- SA-I (slow-adapting type I) in Merkel disks : most easily excited by lower-frequency skin deformations and can respond to sustained deformation
- SA-II (slow-adapting type II) in Ruffini endings : can respond to remotely applied lateral stretching of the skin and can be sensitive to the tangential shear strain to the skin that occurs during object manipulation. [18]

The information is thus relayed to the brain where it is integrated and processed, leading to a response that can be conscious or unconscious. This feedback loop allows organisms to adapt to their environment continuously and to perform complex tasks with precision.

In this section, three examples of the importance of haptic feedback are discussed. This gives us an idea of the importance of this feedback in everyday life and of the importance of analysing the haptic illusion created by gravity in order to better understand and adapt to it.

2.2.1 On the modulation of grasping forces

The synchronisation between GF and LF is studied in [15]. It highlights the critical role of skin receptors on the fingertips and the underlying sensorimotor memory in adjusting grip force during object manipulation. The study presents detailed experiments where subjects lifted objects of varying surface textures (sandpaper, suede and silk) to observe how grip and load forces are coordinated in response to different frictional properties (see Figure 2.7).

The results show that the grip force is modulated in synchronisation with the load force required to lift an object, adjusting based on the object's friction to maintain a minimal safety margin that prevents slipping. For example, slippery objects required increased grip force. This suggests that in scenarios without visual cues, such as lifting an object in the dark, haptic feedback is essential. It is the only means by which individuals can

identify the material and approximate weight of the object and adjust their grip force accordingly.

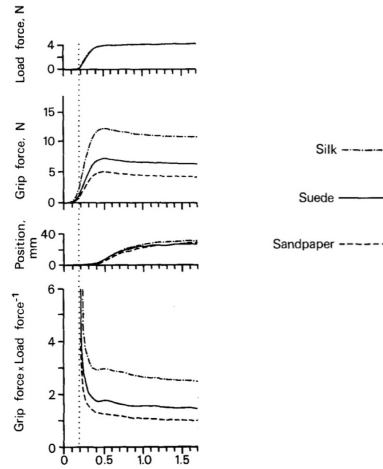


Figure 2.7: Lifting and holding objects with different surface textures [15]

Cutaneous afferent input, particularly from receptors sensitive to touch and pressure changes, is vital for adapting grip force efficiently. This sensory feedback allows for immediate adjustments in grip strength as soon as the object is touched, even before the load force is applied. The study [19] also re-emphasizes the critical role of cutaneous afferents in object manipulation, supporting the notion that cutaneous feedback is vital for the maintenance of a secure grip and adaptation of the grip force/load force ratio based on friction at initial contact. Indeed, they found out that with anesthetized fingers, the object was dropped in 36% of trials, with significant slips in an additional 12% of trials. The study [15] further explores how the brain stores information about previous tactile experiences (sensorimotor memory), which influences how grip adjustments are made in subsequent tasks involving object manipulation. This memory trace allows for a quicker adaptation to familiar textures and weights using the internal models discussed earlier.

A video taken from Roland Johansson Lab in the Department of Integrative Medical Biology of Umea University in Sweden shows the importance of haptic feedback in daily life activities. They injected a lidocaine/bupivacaine anaesthetic into the digital nerves of a woman's thumb and first two fingers and asked her to try to light a match. The injection of the anaesthetic significantly altered the control of grip forces, as the woman struggled to pick up the match. Therefore, it is clear that the impairment of haptic feedback significantly reduces the ability to perform even basic tasks efficiently as grasping an object. Errors in grip force control, due to impaired tactile feedback or misalignment between predicted and actual sensory events, can lead to grasping errors, emphasizing the importance of accurate tactile feedback for successful object manipulation. [18][20]

The study [21] also investigates the relationship between skin-based sensory feedback and grip force control during object handling. It reveals our system's ability to modulate grip forces to adapt to varying object properties such as weight and friction, ensuring optimal interaction even in noisy environments. This adaptability results from the dynamic interplay between sensory input and motor commands, which is crucial for the observed

versatility of grip control.

Even when movements are too fast for sensory feedback to trigger each action sequentially, the nervous system uses internal models informed by sensory input to tailor motor commands to the specific task. The article also demonstrated the importance of such feedback in learning and performing new motor skills, highlighting the essential contribution of cutaneous afferents to the development and maintenance of anticipatory grip force adjustments.

In the research conducted in paper [22], subjects demonstrated the ability to discriminate small differences in tangential force (= load force). It highlights the precise and detailed information that cutaneous afferents provide about forces acting on the skin.

2.2.2 On the use of prosthetic limb

As said before, when we touch an object, several categories of afferent nerve fibres are involved in transmitting sensory signals from the skin to the brain, specifically the somesthetic cortex, which is responsible for the perception of touch and the integration of tactile sensations. This elaborate neural processing allows full recognition of the tactile stimulus. Today's technologies have not yet reached a stage where they can emulate the intricate sensitivity of the human hand. [21]

However, the article [23] highlights the crucial role of haptic feedback for people using upper limb prostheses, noting that it is necessary to perform daily tasks efficiently and safely. The lack of direct hand-related sensory feedback makes object manipulation hard (since the importance of haptic feedback in grasping forces was demonstrated in the previous section), leading to difficulties in grasping without visual monitoring, increased cognitive demands and a greater likelihood of prosthesis abandonment. The review advocates the incorporation of sophisticated haptic feedback systems into prosthetic designs to increase user satisfaction, provide more natural and intuitive prosthetic control and thereby improve device functionality and user acceptance.

When a patient has lost a limb, they can suffer from phantom limb sensations which refer to the feelings that the amputated limb is still attached to the body and functioning normally. Individuals who experience these sensations may feel various painful or non-painful phenomena such as movement, touch, temperature, pressure, vibration and even itchiness where the limb used to be. This is due to the fact that the cortical representation of their absent limb still exists.

The article [24] states that four of the five participants who took part in their experiment reported a reduction in phantom limb pain after using the sensory feedback system integrated into their prosthesis. This observation suggests that non-invasive sensory feedback, by providing somatosensory information corresponding to the phantom hand map on the residual forearm, may contribute not only to improved prosthetic perception but also to a reduction in phantom limb pain. This highlights the potential of sensory feedback systems to improve the psychological and emotional well-being of prosthesis users, in addition to improving the physical functionality of the prosthesis.

2.2.3 On task learning

The study conducted by [25] explores the impact of Virtual Reality (VR) with haptic feedback on enhancing physical examination skills among healthcare students. It addresses the challenges of teaching complex physical examination skills in healthcare education and suggests VR with haptic feedback as a potential solution. The COVID-19 pandemic has further emphasized the need for such technological integration in healthcare education.

The study [26] conducted by Abrar Gani et al., explores the educational benefits of integrating haptic feedback into virtual reality simulations for bone drilling for junior surgeons. It was a block randomised, controlled, double-blinded study involving 31 junior orthopaedic surgeons with limited experience, divided into haptic and non-haptic groups. The study aimed to determine the efficacy of haptic feedback in enhancing drilling task performance, a crucial competence in orthopaedic surgery. Results showed that participants who trained with haptic feedback achieved markedly better outcomes, including more accurate drilling with reduced error margins, despite taking more time to complete the tasks. They also received higher Objective Structured Assessment of Technical Skills (OSAT) scores, which is a standardised assessment tool used in medical and surgical education to measure the technical skills of students or professionals, and executed a greater number of drills safely. These findings suggest haptic feedback in VR simulations can improve surgical training quality, offering more realistic experiences and potentially leading to safer surgical practices. This study highlights the importance of haptic feedback in surgical simulation training, indicating that it can significantly contribute to the skill development of junior surgeons, emphasizing its potential role in facilitating the acquisition of key surgical skills without risking harm to patients.

These three points therefore demonstrate the importance of haptic feedback in modulating grasping forces, but also in rehabilitating patients who need to wear a prosthesis and in learning a task. The existence of a haptic illusion therefore needs to be analysed and understood so that it can be potentially adapted in these different areas.

2.3 Spatial orientation

On Earth, the brain receives many signals about the body's movements and orientation. The interaction between these signals is important to take into account because, as said before, mistakes in perceiving the direction of gravity and the weight of an object can lead to incorrect estimations of the force required to manipulate the object, resulting in haptic illusions where the actual applied force and the perceived force differ.

An understanding of the interaction between spatial orientation, gravity and haptic illusions can influence the design of user interfaces, virtual reality equipment and devices for missions in modified gravity environments. This makes it possible to create systems that compensate for or use these illusions to improve human performance and safety.

2.3.1 Inner ear

The ear is made up of three parts: the outer ear, the middle ear and the inner (or internal) ear. The inner part shaped like a labyrinth is located in the temporal bone and has various organs that can be seen on Figure 2.8 :

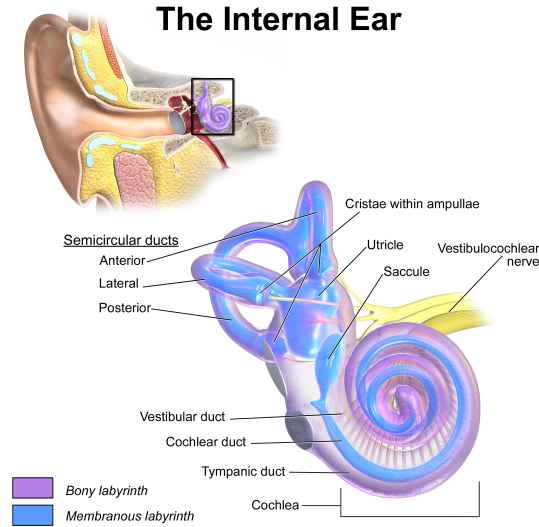


Figure 2.8: Internal ear [27]

- **The cochlea** : dedicated to hearing.
- **The vestibular system** : dedicated to balance. Signals coming from this organ are used by the Central Nervous System (SNC) to control balance and eye movements. They also influence, at a higher level, the conscious perception of verticality. [7][28] Movements of the head are made of two components : rotations and translations. These different components are covered in separate sections.
 - **Otoliths** (= saccule + utricle) : indicate linear accelerations. They detect the orientation of the gravito-inertial acceleration $\vec{R}$ which is a fonction of the linear acceleration and the head tilt that can be seen on Figure 2.9. By detecting the direction of gravity, they help to regulate our sense of balance and stability.

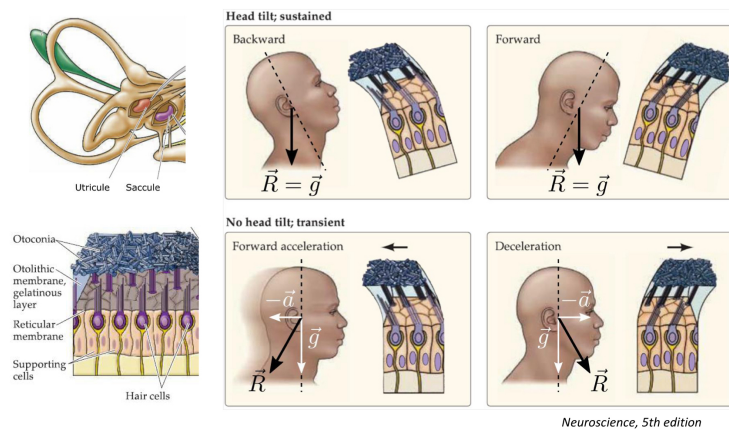


Figure 2.9: Otoliths [7]

- **Semicircular canals** : indicate rotational movements. There are 3 of them and they are sensitive to angular accelerations of the head along 3 quasi-orthogonal axes that can be seen on Figure 2.10.

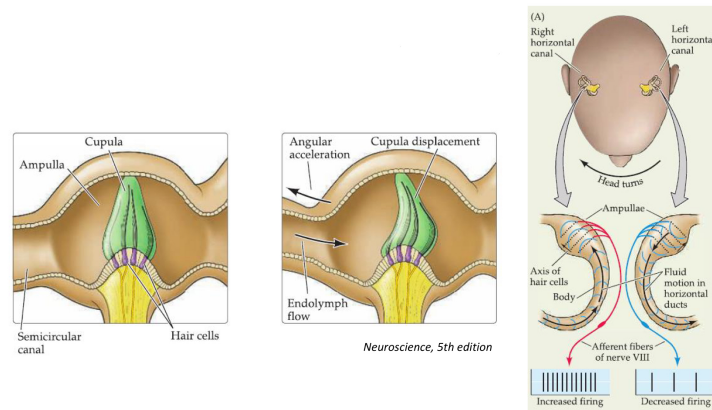


Figure 2.10: Semicircular canals [7]

2.3.2 Visual signals

Many visual cues help us to orientate ourselves and our environment precisely in space. Some of them can be monocular cues (Figure 2.11) that provide depth information even when viewing a scene with only one eye while others can be binocular cues (Figure 2.12) that provide depth information when viewing a scene with both eyes. [29][30]

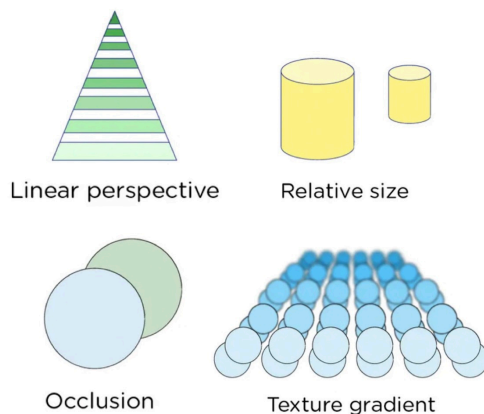


Figure 2.11: Monocular cues [31]

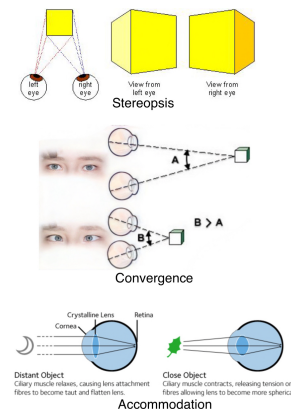


Figure 2.12: Binocular cues [32][33][34]

2.3.3 Proprioception

Proprioception is the sense of self-movement, force and body position. It is mediated by proprioceptors which are mechanosensory receptors located within muscles, tendons and joints. It informs us about the position and the movements of our limbs and the forces exerted by the muscles. This sensory feedback is essential for coordinating movements

and interacting with our environment efficiently. [35]

Two of the most important internal receptors are :

- Muscle spindles that detect changes in muscle length and speed
- Golgi tendon organs that sense changes in muscle tension [36]

and can be seen on Figure 2.13.

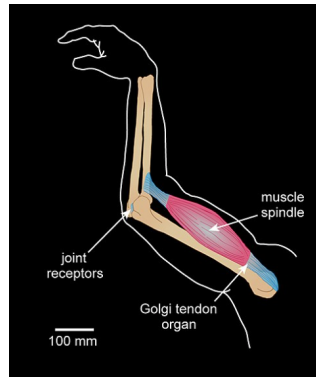


Figure 2.13: Proprioception [35]

The brain utilizes the information from these internal receptors to explore various aspects of physical interaction and internal dynamics, including:

- the influence of gravity on joint torque
- the behaviour of internal organs and body fluids in response to gravitational forces [7]

helping the brain 'sense' the direction of gravity.

These proprioceptors can be used to estimate the orientation of the body, the movements of our limbs and the changes in muscle tension. These signals help the brain to estimate the force required to perform a movement or maintain a position. Indeed, proprioception mechanism informs the brain of the loads applied to muscles and tendons, enabling muscle strength to be adjusted accordingly. For example, if the load on a muscle increases, proprioceptive receptors can detect this increased tension and signal the brain to increase muscle strength to compensate.

When lifting an object, the brain uses proprioceptive signals to adjust the grip force and load force according to the estimated weight of the object and the movements required. It also contributes to muscle memory, allowing the muscles to remember the forces applied during repetitive movements. This can help improve the precision and efficiency of movements over time, as the brain adjusts the force required based on past experience.

The study [37] explores the neural mechanisms that allow humans to maintain a stable perception (named the orientation constancy) of the body orientation, despite frequent changes in head, eyes, limbs and body positions which is crucial for coherent spatial

perception and sensorimotor planning. The research emphasizes the importance of the temporo-parietal cortex (TPC) in integrating sensory information to support orientation constancy. It also underscores the complex interplay between various sensory inputs and the cerebral cortex in maintaining this spatial orientation and the potential disruptions to this sense.

Another study [38] focuses on how humans perceive verticality, integrating sensory information from vision, somatosensory systems and vestibular inputs to form an internal representation of vertical orientation. The study investigates the perception of verticality in different groups. The first one includes healthy individuals, the second one paraplegic patients with complete spinal cord injury resulting in sensory loss in the trunk and lower limbs, and the third one hemiplegic stroke patients with varying degrees of sensory loss on one side of the body. This study highlights the importance of somatosensory information for a robust sense of verticality and the interaction between somatosensory and vestibular inputs in modulating vertical perception. It emphasizes the importance of combining sensory data from different systems to form and refresh the brain's concept of uprightness by showing how the somatosensory and vestibular systems work together to ensure we remain balanced and correctly oriented.

2.4 What happens when gravity changes?

In order to analyse the impact of gravity on the haptic illusion and to investigate why this illusion is amplified in hypergravity and diminished in microgravity, it is important to observe the impact of a change in gravity on our bodies.

2.4.1 Changes in spatial orientation

Visual information is one of the few forms of information that remains intact when gravity changes.

In a zero- or microgravity environment, the otoliths, which help the brain detect linear accelerations, no longer respond to changes in head tilt. This significantly disrupts our sense of orientation, leading to errors in perceiving the force needed for manual tasks and causing haptic illusions where the perceived force does not match the actual applied force.

In space, the brain adapts by interpreting otolith organ signals exclusively as indicators of linear motion. However, upon returning to Earth, this adaptation becomes inappropriate, resulting in temporary balance issues for astronauts as their brains recalibrate to terrestrial gravity. [7]

The study [39] found that if embryon rats are exposed to hypergravity for a long time, the gravitational environment influences the segregation of vestibular axonal terminal fields. This indicates gravity's role in the development of vestibular system connections.

Another study [40] shows that visual cues are increasingly relied upon when vestibular cues become less reliable due to changes in body orientation relative to gravity. Sensory conflicts between visual and vestibular signals can lead to illness.

The proprioception is also modified in microgravity because there is no longer gravitational load force. The absence of gravitational load on the muscles can make it difficult to estimate the force required to manipulate objects. This can contribute to haptic illusions where the perceived force does not correspond to the real force. [7]

2.4.2 Prediction and optimization of movements

Parabolic flights are one of the methods used in research to vary gravity. Parabolic flight is a type of research mission that simulates hypergravity or microgravity by increasing and reducing the weight of the aircraft for a short period of time.[41] The diagram of a parabolic flight can be seen on Figure 2.14.

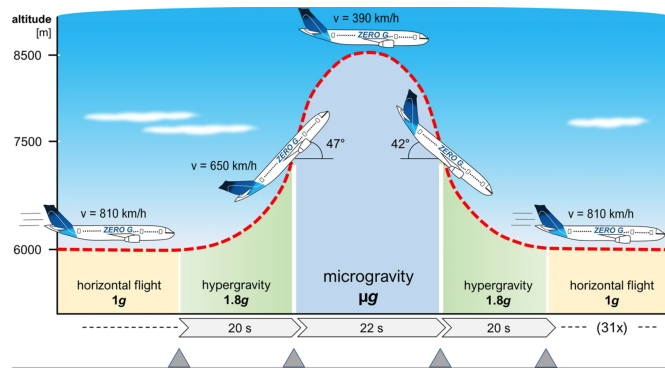


Figure 2.14: Diagram of parabolic flight [42]

Numerous studies carried out in parabolic flights have shown that humans can quickly recalibrate their grip forces in response to changes in gravity. The study [43] shows that the internal representation of arm and object dynamics adapts to new gravitational contexts. It also highlights the fact that humans use forward internal models to predict and adjust grip forces dynamically, allowing efficient object manipulation in the absence of gravitational cues.

Another study [44] using a long-arm human centrifuge shown in Figure 2.15 to vary gravity revealed that participants could effectively adjust their grip forces in different gravito-inertial fields from 1g to 2.5g. This ability to predictively adapt grip forces without prior experience in these conditions underscores the brain's capacity to update its internal models rapidly and accurately, based on integrated sensory inputs.

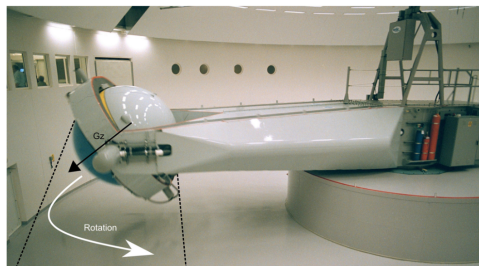


Figure 2.15: Long-arm human centrifuge [44]

Jeremie Gaveau et al. conducted a study [45] that explores how the human brain uses an

internal model of gravity to optimize movement strategies, specifically in arm movements under varying gravity conditions. The study tests the hypothesis that this internal model can be used not only to compensate for gravitational effects but also to exploit them to minimize effort during movement. Under zero-gravity conditions during parabolic flights, initial movements still reflected the patterns seen under normal gravity, indicating that the brain was using its existing model based on Earth's gravity. However, with repeated exposure to microgravity, these directional asymmetries began to diminish (shown on Figure 2.16) , suggesting a gradual recalibration of the internal model to the new environment. This recalibration affects motor planning and can lead to haptic illusions due to discrepancies in the prediction and optimization of movements during this process.

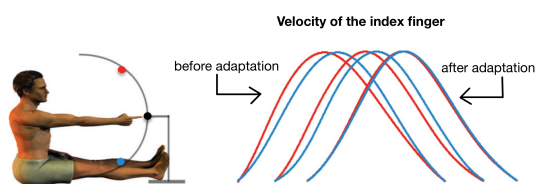


Figure 2.16: Optimisation during parabolic flights - adapted from [45]

The research [46] highlighted how humans adapt their motor strategies to accommodate the increased gravitational forces experienced during hypergravity conditions. By optimizing motor commands based on the action of gravity on the limb, the study illustrates the central nervous system's capability to internalize environmental changes and adjust motor planning accordingly. This capability suggests a sophisticated level of adaptability and planning within the human motor control system, emphasizing the CNS's role in integrating sensory inputs and environmental feedback to optimize motor output.

2.4.3 Haptic illusion created by gravity

As all the concepts necessary to understand the subject have been covered, it is now possible to describe in greater depth the study that led to this master thesis topic.

The isometric force refers to the force generated by a muscle while in a fixed position, meaning the muscle does not change length and no visible movement of the joint occurs, in contrast to isotonic force. Both of them can be seen on Figure 2.17. It is a type of muscular contraction where the muscle exerts force against an immovable object or resistance, leading to tension within the muscle without altering its length.

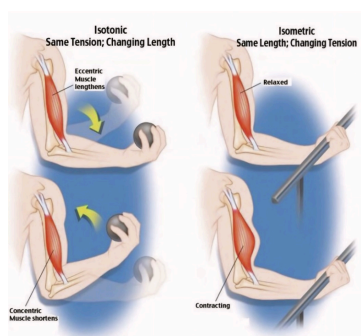


Figure 2.17: Isotonic and isometric forces [47]

The study [6] led by Laurent Opsomer and colleagues delves into the impact of gravity on the control and perception of isometric forces exerted through the fingertips, a key aspect of human dexterity and fine motor control. The primary goal of this research was to determine if the nervous system can accurately replicate remembered isometric load forces (LF) and maintain an adequate GF-LF coupling across various gravito-inertial conditions, despite significantly different proprioceptive feedback and arm motor commands. Eleven participants were trained to apply a specific LF in upward and downward directions, indicated by LEDs, using a dynamometer as shown on Figure 2.18. An auditory feedback was triggered when the required force was applied.

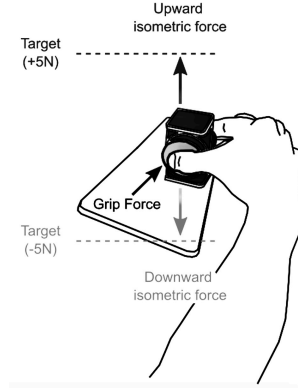


Figure 2.18: Task [6]

Trained participants reproduced the learned LF, first on the ground and during level flight (1g) and after during parabolic flights made up of different phases of hypergravity (1.6g) and microgravity (0g).

The results that can be seen on Figure 2.19 show that gravity influences the asymmetric of LF between the upward and downward movements but does not influence GF, which is supposed to be adapted to LF to avoid slips. Indeed, GF was always similar whether LF was produced upward or downward, indicating that they were not tuned.

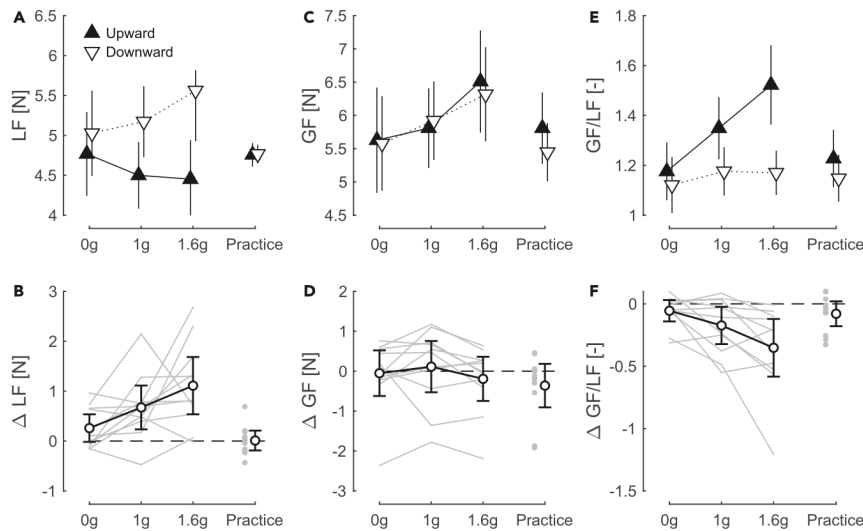


Figure 2.19: Graphs showing the haptic illusion [6]

These results show that participants think they are exerting the same force as GF does not vary, but in fact they are not, as reproduced LF had consistently larger downward magnitudes than upward magnitudes even in a 1g condition.

Therefore, the study shows that gravity creates the illusion that upward forces are larger than downward forces. This haptic illusion, considered by the authors as an overestimation of upward forces and/or an underestimation of downward force, disappears in microgravity and is increased in hypergravity. They explained it as possibly related to the muscular effort which is necessarily biased by gravity as explained before. If muscular effort contributes to force estimation, this may explain why asymmetrical load forces (LFs) under 1 g conditions were observed and why these asymmetries diminished in 0 g conditions.

Their results also showed a temporal correlation between GF and LF that was maintained during parabolic flights but highlighted a decoupling between GF and LF in terms of force magnitude across the various gravity levels. [6]

Interest in investigating the haptic illusion created by gravity

Since it has been discovered that a haptic illusion exists, even on Earth, it seems essential to investigate these results further. Indeed, as explained before, haptic feedback is essential in everyday life. If it is misinterpreted by the subject, this poses a problem.

A better understanding of this haptic illusion could help to design human-machine interfaces that take it into account, especially in environments where gravity is modified, such as in space. This would ensure a more natural and precise interaction with tools and interfaces.

The study [48] shows how adapted haptic parameters can help overcome sensorimotor deficits induced by microgravity, particularly during the early phases of space adaptation. This is crucial for astronaut performance, especially when using controls or tools that require high precision.

As well as being of interest for space missions, a deeper understanding of this phenomenon could also be useful for other human-machine interfaces used daily. For example, paper [49] shows that by better understanding how forces are perceived differently under different conditions, surgical tools can be designed to provide better force feedback, which is crucial for tasks that rely heavily on tactile accuracy. In addition, by increasing the forces appropriately, surgeons can operate with greater confidence in their movements, potentially reducing fatigue and increasing efficiency during long procedures.

As part of this master thesis, the objective was to further investigate haptic illusions through an experimental study. I chose to examine the impact of the direction of isometric force and body orientation on the variation of the Load force and the Grip force.



Chapter 3

Materials and methods

The aim of this chapter is to explain in details the experiment that has been carried out for this master thesis. This part is crucial because it allows other researchers to replicate the study providing enough details about the experimental design, materials, equipment and procedures used. This is fundamental for scientific rigor and the validation of results.

3.1 Design of the experiment

As part of this work, it was decided to carry out an experimental research using a protocol with different participants. This experiment was carried out in the UCLouvain laboratory in the COSY pôle in the campus of Woluwe.

Each experimental procedure is divided in different steps :

1. Presentation and resources :
 - Aim of the experiment
 - Material
 - Panel of participants
2. Experimental protocol and hypotheses
3. Data collection and processing
4. Statistical analysis

3.2 Presentation and resources

This section is dedicated to presenting the research question that we hope to answer through this experiment, as well as the equipment needed to carry it out and the panel of participants who took part of it.

3.2.1 Aim of the experiment

In order to investigate the haptic illusion created by gravity, the question to be addressed in this experiment is as follows:

Questions

Is there a difference in the variation of Load Force and Grip Force when the isometric force is made perpendicularly to the gravity?

Does the orientation of the body influence the variation of LF and GF?

3.2.2 Material

Equipment from the laboratory was used in the experiment and is detailed below.

A. Rotating chair

The 360° rotating chair that can be seen on Figures 3.1 and 3.2 was used to vary the subject's position in relation to the axis of gravity.

This chair can be incremented in steps of 15 degrees. When it is rotated, the whole frame rotates with it, so that the subject is always facing the device with the dynamometer and the LEDs (which are presented below).

Thus, the position of the arm is always the same, whatever the orientation of the chair.

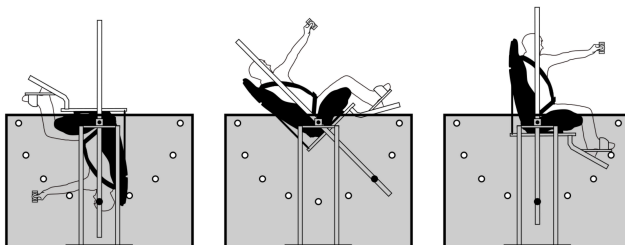


Figure 3.1: Scheme of the rotating chair [7]



Figure 3.2: Rotating chair

B. Dynamometer

A dynamometer is used in biomechanics and physiology to measure muscle strength, such as hand grip strength. It allows to collect the forces and torques data applied to it and can be seen on Figures 3.3 and 3.4.

It is made up of :

- 2 force-moment sensors (Mini 40 F/T transducers, ATI Industrial Automation, Apex, NC, USA) measuring 40mm in diameter : one for the thumb and one for the index finger
- 2 humidity circular printed circuit boards (PCB) sensors, glued on top of the force-moment sensors. Also 40mm in diameter, with sensitive electrodes located in a circle 10mm in diameter around the centre of the PCB.

During this experiment, the dynamometer is static and placed on a plate attached to the frame that moves when the chair rotates.

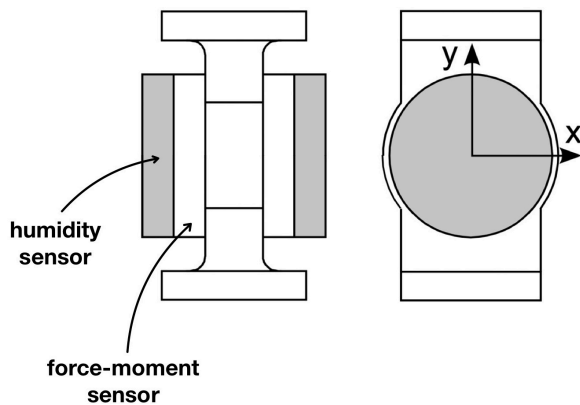


Figure 3.3: Scheme of the dynamometer [50]



Figure 3.4: Dynamometer

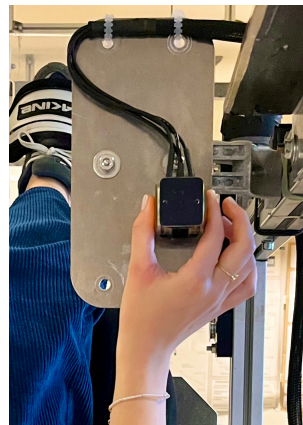


Figure 3.5: Dynamometer

C. LEDs

A set of LED lamps (see Figure 3.6) is attached to the frame to indicate the direction of the isometric force to be performed.

They are used during the experiment to indicate the up/down or forward/backward direction of the force to the participant. Thus, the lamps light up alternately for a certain length of time.

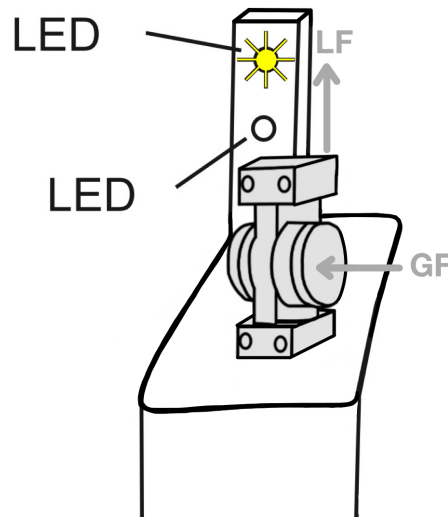


Figure 3.6: LED lights and static dynamometer

D. Signal conditioner

Signal conditioning is a process used in various engineering and scientific applications to prepare signals for further processing or analysis. It is usually used to do a first amplification, filtration, isolation and conversion of the raw signal.

Here, it filters the signal sent by the dynamometer and sends it to the acquisition card in the computer.

It also emits a sound signal (feedback) via the metronome when the target isometric force indicated in the software programme is reached.

E. Experimental set-up

The Figure 3.7 shows the experimental set-up for the experiment carried out, including the different elements presented above : the rotating chair, the dynamometer, the LED lamps and the signal conditioner. In addition, there is also the computer showing the software programme used and the metronome. The links between the different elements and their roles are shown in red.

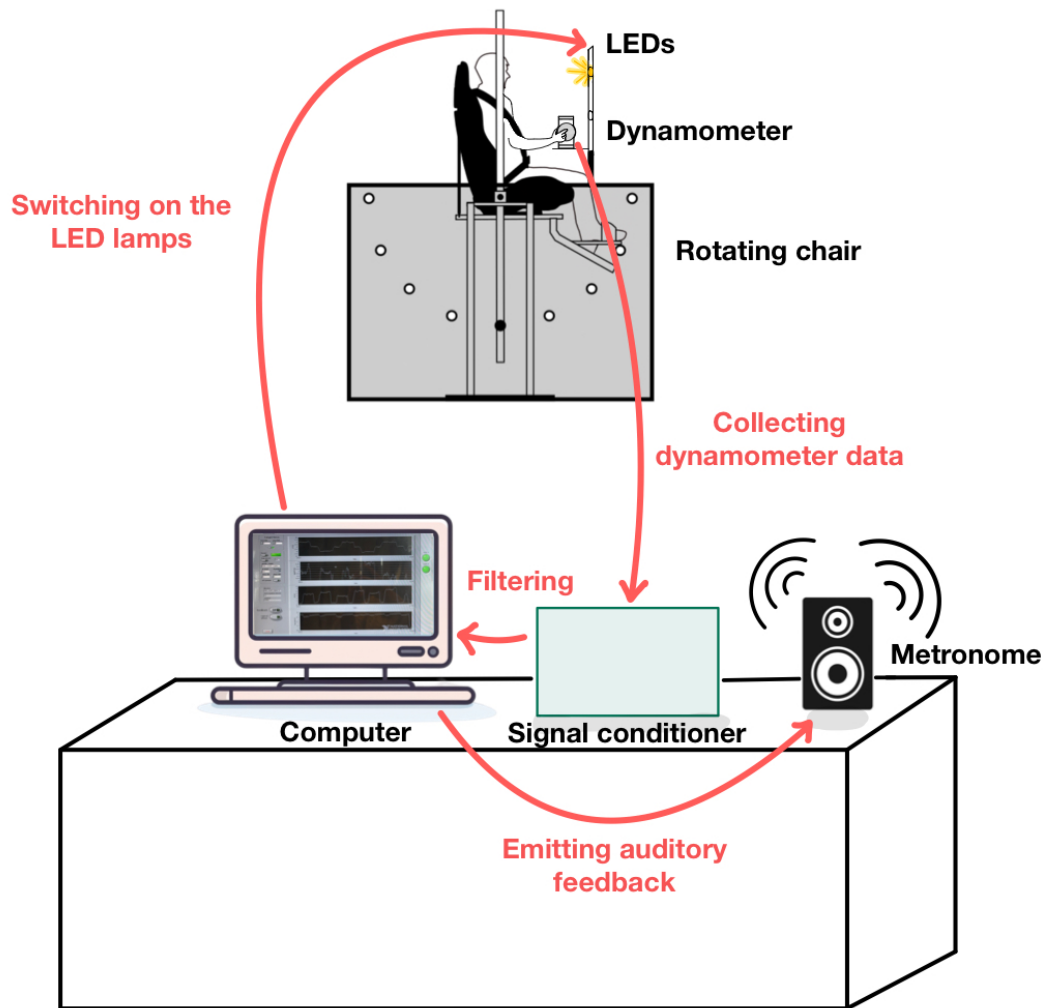


Figure 3.7: Experimental set-up

3.2.3 Panel of participants

A group of 15 healthy humans participated in this experiment. All participants are between 17 and 56 years old. Among them, 6 are females and 9 are males.

Only one of the participants is left-handed.

All participants were volunteers and signed a consent form which was read with them and they all received a copy of it. They were asked to sleep well the night before the experiment and not to be under the influence of alcohol or drugs.

3.3 Experimental protocol and hypotheses

As a reminder, the two questions to be answered by this experiment are as follows :

- Is there a difference in the variation of Load Force and Grip Force when the isometric force is made perpendicularly to the gravity?

- Does the orientation of the body influence the variation of LF and GF?

3.3.1 Observables

The observables are the coefficient of friction and the variation of the Load force (LF) and the Grip force (GF).

3.3.2 Protocol

When the participants arrive, they are asked to wash their hands with water and soap. The time required to explain them the experiment allows the skin to regain its natural hydration level.

The experiment is divided in 2 different parts. The first one collects the data for the calcul of the coefficient of friction. This step is also repeated at the end of the experiment. The second task requires the participants to perform the designated movement, repeating it across various conditions. These tasks, along with the overall structure of the protocol, are explained to the participants in advance.

A. Coefficient of friction

The aim of this first part is to see if the coefficient of friction in one direction is the same than in the opposite direction. If there is a difference, it can explain variation in Grip force and/or Load force.

This test will be performed at the beginning and at the end of the experiment in both of the set of directions (upward/downward and forward/backward). As the moisture of the fingers can have an impact on the results, it is therefore important to see if the coefficient varies during the experiment.

The participants are asked to pinch the fixed dynamometer and perform vertical upward and downward (see Figure 3.8) or horizontal forward and backward movements with their hand at moderate speed without releasing their grip.

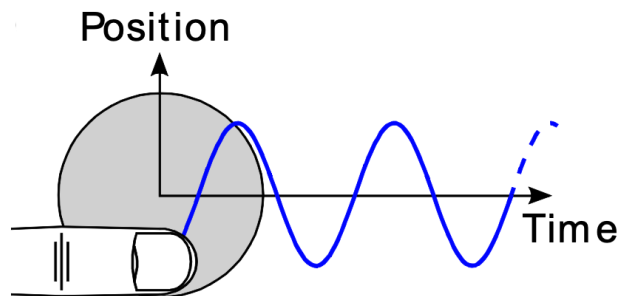


Figure 3.8: Task of friction in vertical movements [50]

CHAPTER 3. MATERIALS AND METHODS

The subjects were asked to perform this sequence of movements three times with three different grip forces for each set of directions :

- low : $\pm 1\text{N}$
- medium : between 2 and 3N
- high : more than 5N

and to try to keep the force constant.

B. Execution of isometric forces

First, there is a pre-training phase during which subjects can familiarise themselves with the device, including the LED lamps and the auditory feedback. They can test 2 blocks of 10 trials in the two sets of directions to make sure they have understood how it works.

After this pre-training phase, the second part of the experiment proceeds as follows. Four conditions are tested :

- two sets of directions : **isometric upward and downward forces** or **isometric forward and backward forces**
- with two body orientations : seated or supine.

These four conditions are carried out randomly for each subject, in order to avoid any potential learning along the experiment that could be reflected in the data.

In each condition, the subject performs 8 blocks of 10 trials :

- 4 blocks of 10 trials **with** auditory feedback (**training phase**)
- 4 blocks of 10 trials **without** auditory feedback (**reproducing phase**)

and these 8 blocks are performed by alternating a block **with** auditory feedback with a block **without** auditory feedback, and so on.

Each of the 10 trials that make up 1 block lasts 2 seconds, followed by an intertrial break of 1 second.

Participants are asked to apply upward and downward or forward and backward isometric LFs of 5 N in a precision grip on the static dynamometer fixed to the support.

During blocks with auditory feedback : At regular intervals, the target LF is communicated via an auditory feedback cue, namely a beep that is emitted whenever the LF magnitude is within the range of 4–6 N. The LED display indicates the direction of LF to produce and the time the LF needs to be maintained.

During blocks without auditory feedback : The participants are asked to reproduce the memorized LF when the auditory feedback is off. The LED display is still activated to maintain the same rhythm.

C. Structure of the experiment

The global structure of the experiment is as follows (bearing in mind that the order within each column is randomised) :

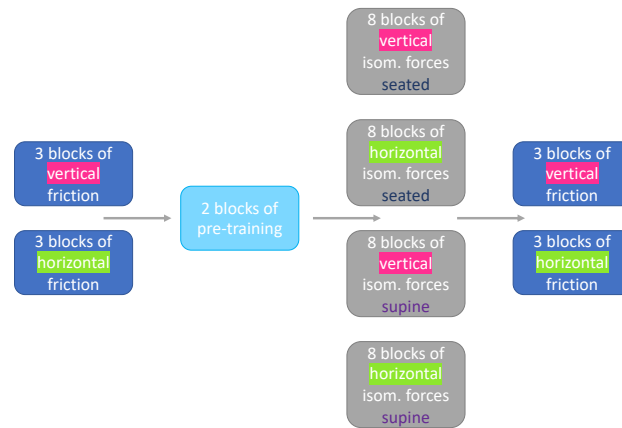


Figure 3.9: Structure of the experiment

and can be seen in more detail on the Figure 3.10.

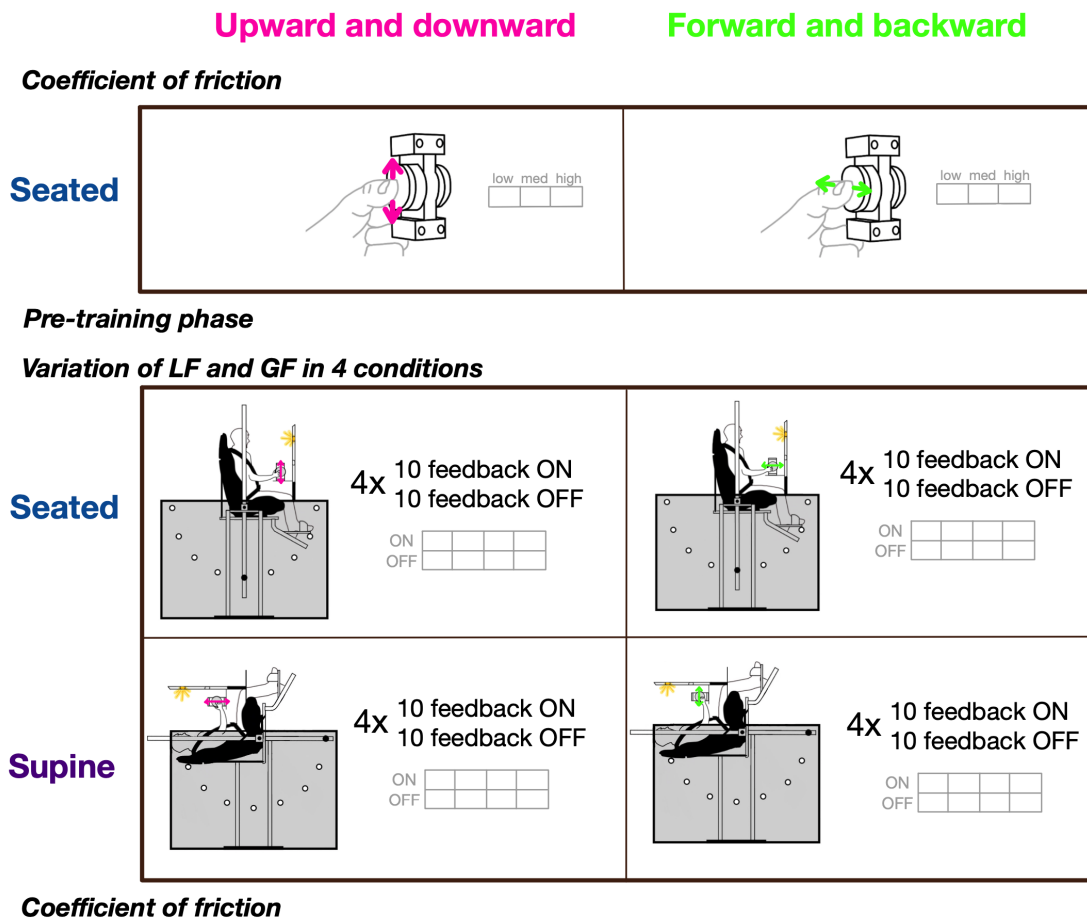


Figure 3.10: Experimental protocol

D. Hypotheses

As already explained in the study [6] by *L. Opsomer et al.*, gravity seems to create the illusion that upward forces are greater than downward forces. It has also been demonstrated that this illusion disappears in microgravity and is increased in hypergravity. It has been shown that downward LF increased significantly with gravity level. On the contrary, GF did not differ significantly between upward and downward trials so a decoupling between LF and GF has been observed and the GF/LF ratio was then not constant across directions and G-levels.

Here, it can be supposed that, in the case with the participant seated, the same results will be observed during the procedure with **isometric upward and downward forces**, since the protocol is similar to the one used in the article. However, for the procedure with **isometric forward and backward forces**, if the coefficient of friction is symmetric, we can imagine that the results will be different. Indeed, as the forces will be exerted perpendicularly to gravity, we should no longer observe differences in LF between the two directions. The GF/LF ratio should therefore be constant. In fact, if there is no haptic illusion, we would expect the GF to be scaled relative to the LF and therefore not have any influence of the direction on the LF and GF coupling.

When the participant is in a supine position, the opposite results should be observed as the upward and downward forces are perpendicular to gravity and the forward and backward forces are parallel to gravity.

3.4 Data collection and processing

This section explains how the data was collected and analysed for the different parts of the protocol.

First of all, some codes are used to extract and do a first processing of the signals by filtering and differentiating the data acquired with the dynamometer.

This data can then be used in different ways depending on the part of the experiment for which it is collected.

3.4.1 LF and GF processing

This sub-section explains the stages involved in the visualisation and processing the data generated during the isometric force tests in the 4 conditions.

A. Data observation

In order to understand the data and check that there are no major anomalies, it is important to be able to observe them. The Figure 3.11 are the types of figures that are generated to help visualise the data. The LED, the LF, the GF and the center of pressure (COP) can be seen.

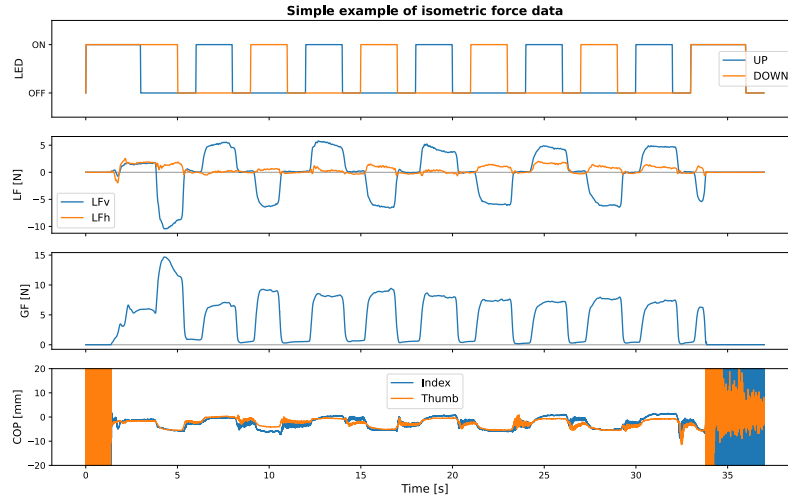


Figure 3.11: Data visualisation

B. Determination of plateaus

The values of interest to us are those within the plateau phase of LF of each trial. The forces are averaged within each plateau phase found.

The delimitations of these plateaus can be seen on the Figure 3.12 with the red dotted lines (---).

In this example, the participant was in a seated position and was doing upward and downward forces so the plateaus are determined in the LFv (—)

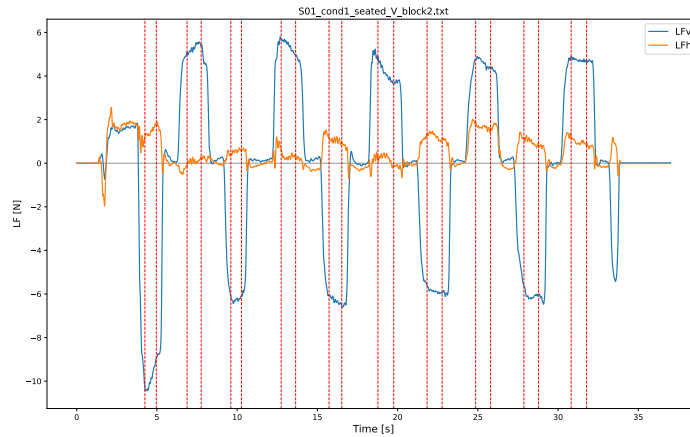


Figure 3.12: Determination of the plateaus

C. Generation of a data table

Once all these plateaus had been determined, the variables of interest were collected for each of these (normally 10 plateaus per block, unless some were excluded because

they were too short, for example). All this data was then placed in a .csv table. This table contains all the values we need to know about a plateau : the number of the participant, the condition number, the body orientation, the set of directions of the isometric forces, auditory feedback (training) or no auditory feedback (reproducing), the block number, the trial number within that block and then all the forces collected thanks to the dynamometer.

With this table, the data is now classified in such a way that it can be easily used to generate graphs and produce statistics.

3.4.2 Coefficient of friction processing

As explained above, the calculation of the coefficient is essential because if a difference in its value is observed between the two opposite directions, this can have an impact on the variation in the GF and/or LF.

The article [50] presents a new method to measure μ_{static} while accounting for the effect of GF. This method allows for continuous estimation of μ_{static} during complex object manipulation, utilizing the relationship between μ_{static} and GF established prior to manipulation. It also explains an algorithm designed to automatically identify the onset of slip in the data, facilitating the computation of μ_{static} . This coefficient of friction μ_{static} is expressed as a negative power law :

$$\mu_{static} = k(GF)^{n-1} \quad (3.1)$$

The steps of this method are the following ones [50] :

1. Find the "useful zones" in each movement where the slip is expected to occur in order to identify slip onset (which refers to the point at which the object being gripped begins to slip or move). A threshold delimiting useful zones beyond and above half the range of the sensor is determined to be sure that each zone would be sufficiently large to include the slip onset of the corresponding movement. The definition of the useful zones (white) and the no-research zones (grey) can be seen on Figure 3.13.

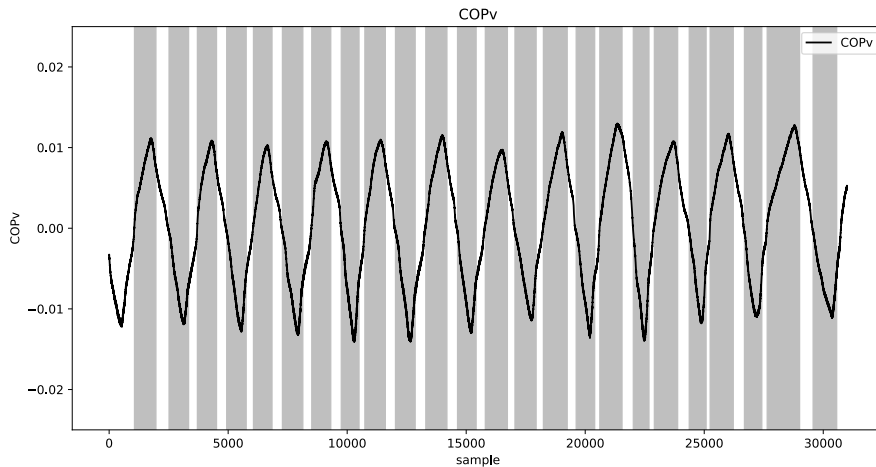


Figure 3.13: Definition of the useful zones in white

2. By observing the ratio of tangential to normal force, it can be identified when the static friction limit is reached, indicating the onset of slip. Thus, looking for the maximum $\frac{LF}{GF}$ in each zone characterises the pair (μ, GF) to be selected. These pairs can be seen on Figure 3.14, with red dots representing the pairs found during upward or forward movements and the blue dots representing the pairs found during downward or backward movements.

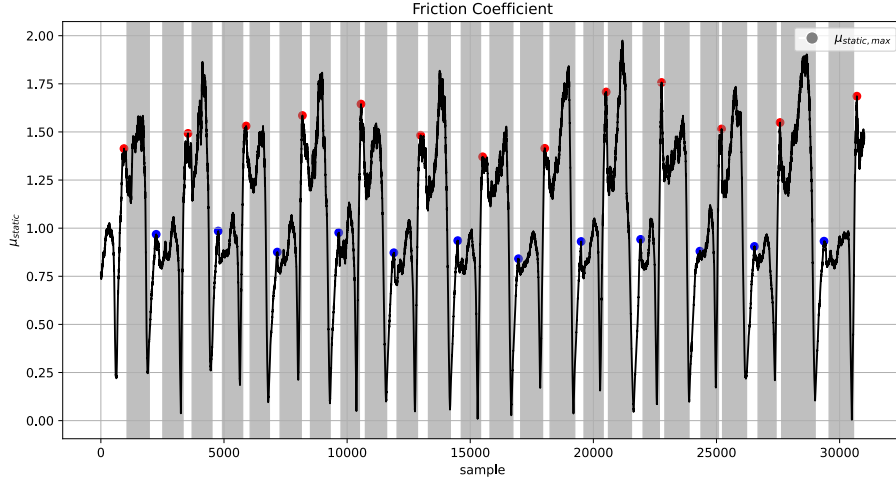


Figure 3.14: Identification of the pair (μ_{static}, GF) in each useful zone

3. Fit parameters k and n can be obtained by using an ordinary least-squares regression procedure based on the equation 3.2 :

$$\log(\mu) = \log(k) + (n - 1)\log(GF) \quad (3.2)$$

The fits can be seen on the Figure 3.15, with the black line representing the fit for all the data (from the 3 sets of grip forces done in this condition), the red line representing the fit for all the upward or forward data (here upward) and the blue line representing the fit for all the downward or backward data (here downward).

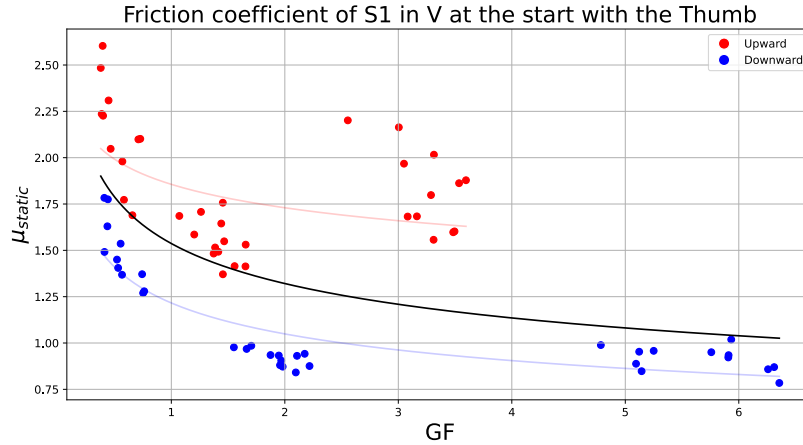


Figure 3.15: Pairs (μ_{static}, GF) in each useful zone for the 3 sets of grip forces

This method is used to calculate k and n for each finger : the thumb and the index finger at the start end end of the experiment.

3.4.3 Slip force

The slip force refers to the force required to initiate slipping of an object that is being held or manipulated, such as with fingers. In the context of grasping an object with fingers, slip force is the critical force at which the object begins to move relative to the fingers holding it. It can be calculated with :

$$F_{slip} = \frac{LF}{\mu_{static}} \quad (3.3)$$

Using the fits generated for each subject, direction, moment and finger, the values of k and n were determined. Consequently, the μ_{static} can be calculated for a given grip force (GF) using the formula 3.1.

Then, for each plateau, the μ_{static} is calculated using the mean grip force (GFmean) on that plateau.

The slip force F_{slip} can then be calculated using the μ_{static} obtained and the mean load force (LFmean) on that plateau.

3.4.4 Safety margin

In the context of gripping objects with fingers, the safety margin SM refers to the additional force applied beyond the minimum required slip force to ensure a secure grip and prevent unintentional slipping or dropping of the object. It can be calculated with :

$$SM = \frac{GF}{F_{slip}} - 1 \quad (3.4)$$

This safety margin is calculated for both the index finger and the thumb, as the normal force can differ between the two due to isometrics. The smaller of the two is then selected as the final safety margin, since our goal is to prevent slippage on either the thumb or the index finger.

3.5 Statistical analysis

Various statistical analyses were conducted.

The repeated measures ANOVA technique has been used because the same participants are subjected to different conditions. This method controls for individual differences by comparing each participant against themselves across conditions, enhancing the sensitivity of the analysis. As a result, it reduces within-subject variability and increases

statistical power, making it easier to detect significant effects with a smaller sample size. This approach efficiently utilizes resources and provides more precise estimates of the condition effects.

T-tests have also been employed as a fundamental statistical tool to examine the difference between two means or to assess the significance of a single mean against a hypothesized value, often zero.

The use of these statistical techniques is detailed below. All analyses were conducted with a significance level of 5% (p-value < 0.05).

3.5.1 Evolution of the forces

Paired t-tests were carried out to observe the evolution of forces :

- Within trials of the same block by comparing the first 5 and last 5 trials of a block
- Within blocks of the same condition by comparing the first 4 and last 4 blocks of a condition

3.5.2 Coefficient of friction

One-way repeated measures ANOVAs have been conducted to test the difference between the μ_{static} at the beginning and end of the experiment, for vertical and horizontal movements, for both the index and the thumb.

One-way repeated measures ANOVAs have been conducted to test the anisotropic nature of the μ_{static} (i.e., the difference between the μ_{static} in the four directions) for both the index and the thumb.

If the ANOVA to test the anisotropy has a p-value less than 0.05, it means that there is at least one value that is significantly different from the mean of the 4 values (the 4 movements). The important thing is to compare the μ of upward and downward movements, and those of forward and backward movements. Therefore, a post-hoc analysis is conducted¹ using two T-tests to compare the movements of interest, with a corrected significance level divided by two (since there are 2 comparisons to be made), equivalent to 2.5%. This approach helps avoid a Type I error (false positive) and maintains a p-value that accurately reflects the probability of making a mistake.

3.5.3 Global analysis

Two-way repeated-measures ANOVAs have been used to test the effect of body orientation, the effect of the set of direction and their interaction on ΔLF_{mean} , ΔGF_{mean} , $\Delta \frac{GF}{LF}_{mean}$ and $\Delta Safety$ margin, both during **training** and **reproducing** phases.

¹A post-hoc analysis allows trends to be found after the end of the study and to find results that were not the primary objective. Thus, any analysis performed after the end of an experiment that was not planned in advance is considered a post-hoc analysis.

After, two-way repeated-measures ANOVAs have been used to test the effect of body orientation, the effect of the state (training or reproducing) and their interaction on the four Δ s for both vertical and horizontal directions.

Student's t-tests have also been used to determine if the Δ s are significantly different from one body orientation to another, for each set of direction.

3.5.4 Detailed analysis

Finally, T-tests were carried out for each condition during both phases to test the significance to 0 of LFmean and GFmean.



Chapter 4

Results

This chapter presents the different results of the experimental study described in Chapter 3.

As part of this master thesis, it was decided to look, in relation to the study [6], at the difference (noted hereafter Δ) between forces in one direction and the other within the same direction set.

Thus, later in this paper, when it is written Δx , that represents :

- $x_{downward} - x_{upward}$ if the direction of movement is **vertical** (relative to the reference frame fixed to the participant, i.e. vertical direction always means head-to-toe movement, whatever the orientation of the body)
- $x_{backward} - x_{forward}$ if the direction of the movement is **horizontal** (relative to the reference frame fixed to the participant, i.e. horizontal direction always means forward-backward movement, regardless of body orientation)

4.1 Evolution of forces throughout the experiment

Firstly, it is interesting to examine the progression of forces throughout the experiment. Two distinct patterns of evolution can be observed:

- The evolution of forces across trials within the same block
- The evolution of forces across blocks within the same condition

4.1.1 Within the trials of a block

The first focus is on the evolution of forces within trials of the same block. To do this, as explained in Chapter 3, a paired t-test was conducted to examine if there is a significant difference between the first 5 and last 5 trials of a block for each condition. The results can be seen on Table 4.1.

As you can see from the table, there are only 2 p-values that are smaller than 0.05. The one of GFmean in **reproducing** in the seated - H condition and the one of GFmean in **training** in the supine - H condition. This means that there is a significant difference between the first 5 and the last 5 trials in the block for these two conditions.

State	Body orientation	Set of direction	Measure	Statistic	p-value
Training	seated	V	LFmean	1.8553	0.0847
Training	seated	V	GFmean	1.3988	0.1836
Reproducing	seated	V	LFmean	1.3796	0.1893
Reproducing	seated	V	GFmean	2.0265	0.0622
Training	seated	H	LFmean	2.0688	0.0576
Training	seated	H	GFmean	-1.1057	0.2875
Reproducing	seated	H	LFmean	0.4210	0.6801
Reproducing	seated	H	GFmean	-2.5697	0.0223
Training	supine	V	LFmean	-0.5563	0.5868
Training	supine	V	GFmean	-1.5806	0.1363
Reproducing	supine	V	LFmean	-0.9706	0.3482
Reproducing	supine	V	GFmean	0.0221	0.9827
Training	supine	H	LFmean	1.0741	0.3010
Training	supine	H	GFmean	-2.8341	0.0133
Reproducing	supine	H	LFmean	1.5772	0.1371
Reproducing	supine	H	GFmean	-0.2090	0.8374

Table 4.1: Results of paired t-test evolution of forces in trials within block

The two evolutions of GFmean in these conditions can be seen on Figures 4.1a and 4.1b. These figures show that in both conditions, GFmean tends to increase during the blocks.

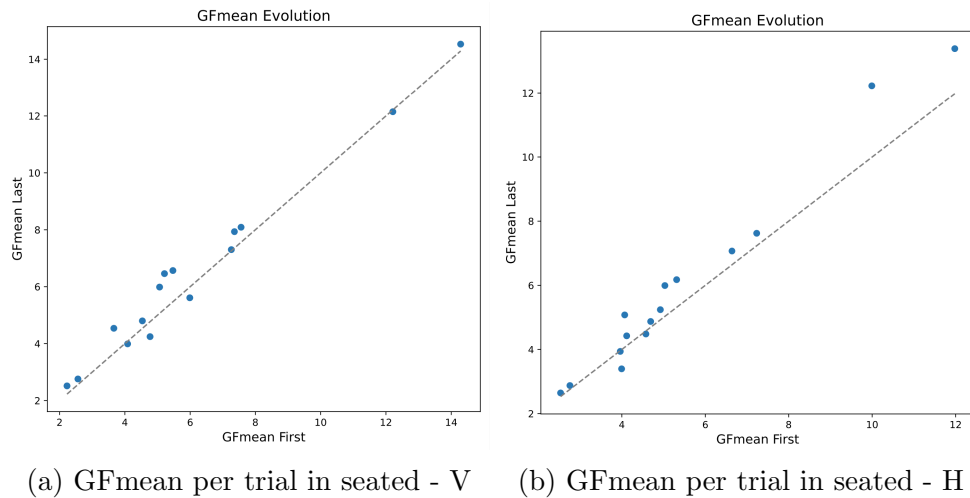


Figure 4.1: GFmean evolutions

4.1.2 Within the blocks of a condition

The second focus is on the evolution of forces within blocks. As for the previous point, a t-test was carried out to examine whether there was a significant difference between the first 4 and last 4 blocks of the same condition. The results can be seen on Table 4.2.

As it can be seen from the Table 4.2, no p-value is smaller than 0, meaning that there is no significant difference between the LFmean or GFmean of the blocks at the beginning and those at the end of a condition.

State	Body orientation	Set of direction	Measure	Statistic	p-value
Training	seated	V	LFmean	0.1406	0.8902
Training	seated	V	GFmean	1.5328	0.1476
Reproducing	seated	V	LFmean	0.8903	0.3883
Reproducing	seated	V	GFmean	1.8539	0.0849
Training	seated	H	LFmean	1.1444	0.2717
Training	seated	H	GFmean	-0.7848	0.4456
Reproducing	seated	H	LFmean	0.3783	0.7109
Reproducing	seated	H	GFmean	-0.1835	0.8570
Training	supine	V	LFmean	0.5992	0.5586
Training	supine	V	GFmean	-0.2122	0.8350
Reproducing	supine	V	LFmean	0.6255	0.5417
Reproducing	supine	V	GFmean	0.3354	0.7423
Training	supine	H	LFmean	1.0140	0.3278
Training	supine	H	GFmean	-0.4131	0.6858
Reproducing	supine	H	LFmean	0.4033	0.6928
Reproducing	supine	H	GFmean	-1.0572	0.3083

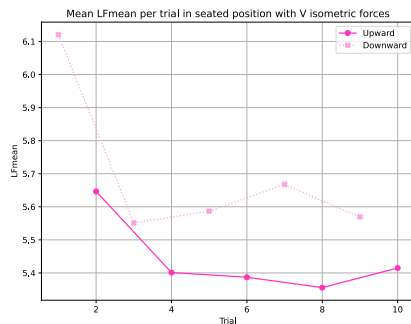
Table 4.2: Results of paired t-test evolution of forces in blocks within condition

4.2 Evolution of Δ LFmean and Δ GFmean throughout the experiment

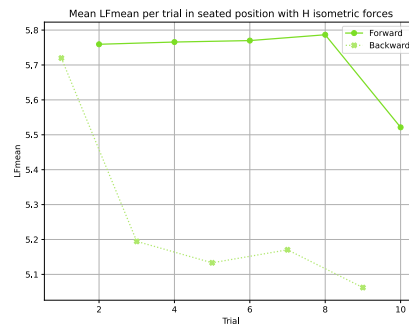
Secondly, it is important to examine if the Δ values fluctuate a lot during the trials. Indeed, if the slopes of the forces in one direction and the other are opposite, averaging all the trials could potentially "erase" the visible Δ at the end of the block. However, if there is a difference in the Δ during the last trials, it is interesting to be aware of it because it is when the subjects have the least recall of what they learned during the training.

4.2.1 Δ LFmean

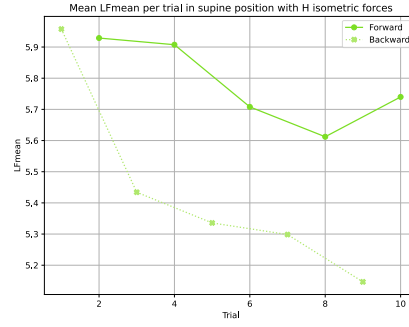
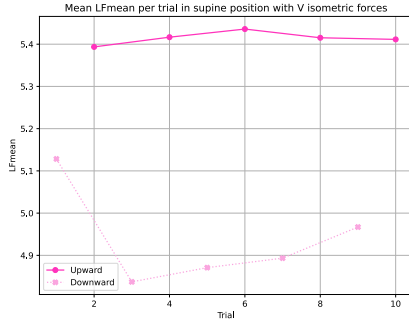
It can be seen on Figure 4.3 that the Δ LFmean does not vary significantly over the trials and the slopes are not crossing each others. Thus, averaging all the trials does not hide different behaviour when the subject remembers the training phase the least.



(a) LFmean per trial in seated - V



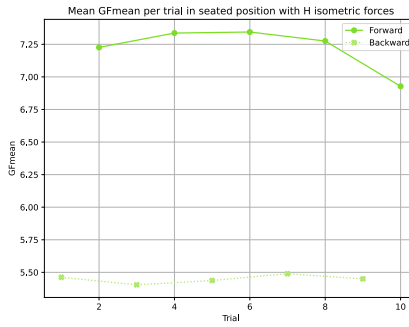
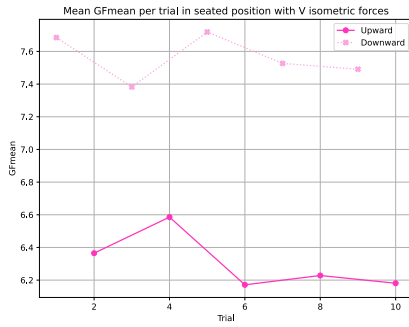
(b) LFmean per trial in seated - H



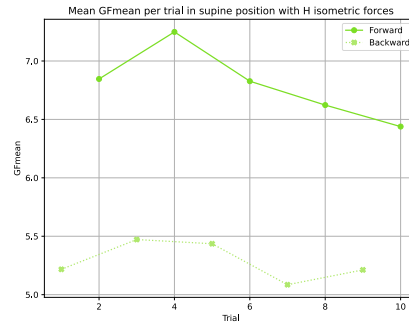
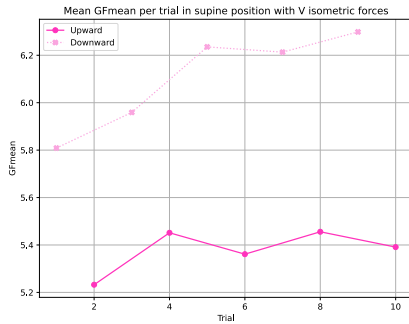
(c) LFmean per trial in supine - V (d) LFmean per trial in supine - H

Figure 4.3: Evolution of Δ LFmean during trials

4.2.2 Δ GFmean



(a) GFmean per trial in seated - V (b) GFmean per trial in seated - H



(c) GFmean per trial in supine - V (d) GFmean per trial in supine - H

Figure 4.4: Evolution of Δ GFmean during trials

As precedently, the Δ GFmean does not vary significantly over the trials. As neither of the two Δ varies much, it is acceptable to average along all the trials.

4.3 Coefficient of friction

The friction coefficients for both the horizontal and vertical directions were calculated for the index and the thumb at the start and end of the experiment, using the method detailed in Chapter 3.

4.3.1 Fits

As an example, the results for subject 1 under each condition are shown below. The graphs depict on Figure 4.5 the μ_{static} depending on GF, with the different fits.

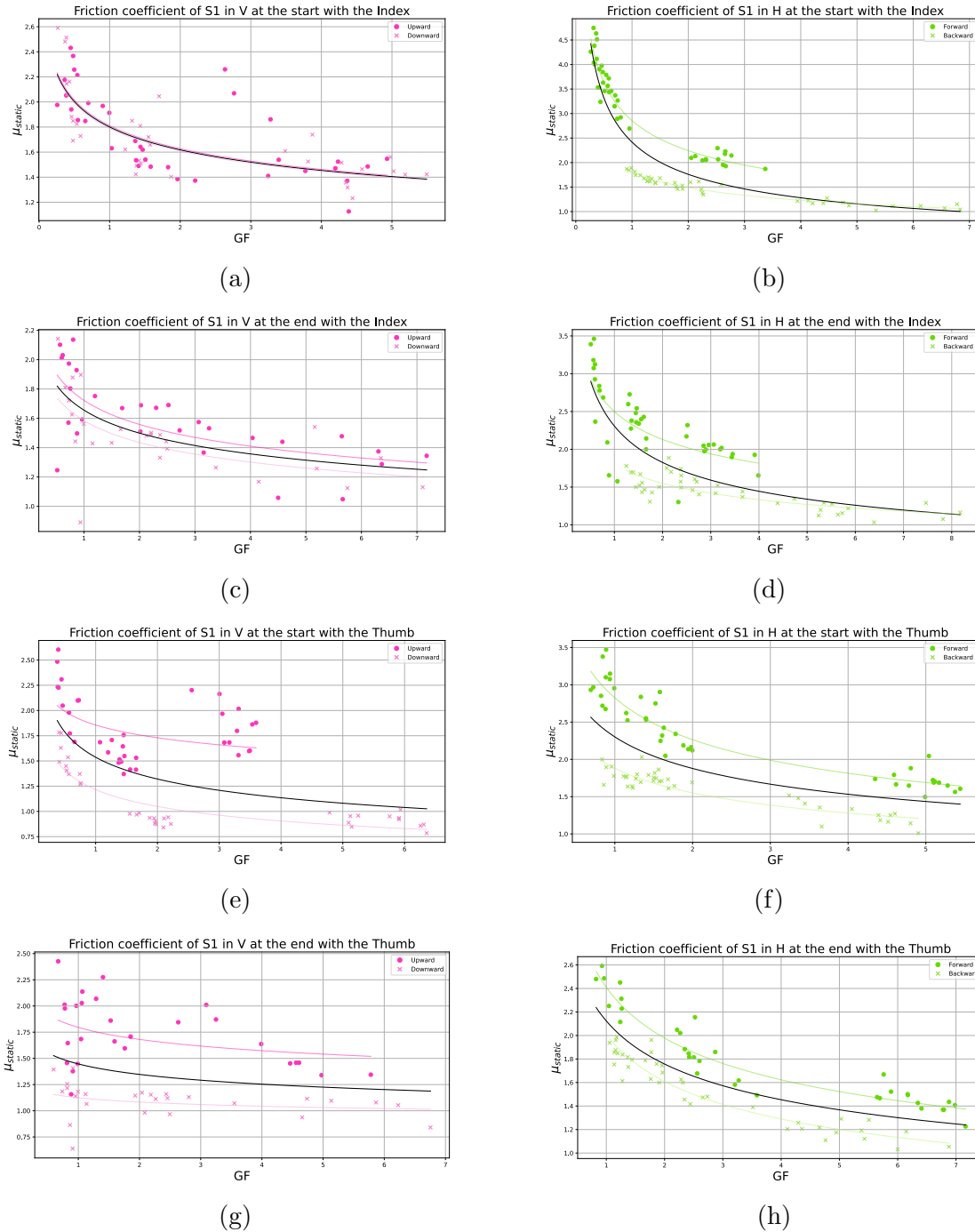


Figure 4.5: Coefficients of friction for (a) Index V at start, (b) Index H at start, (c) Index V at end, (d) Index H at end, (e) Thumb V at start, (f) Thumb H at start, (g) Thumb V at end and (h) Thumb H at end

4.3.2 Difference between start and end

Firstly, it is important to examine the changes in μ_{static} from the beginning to the end of the experiment for both fingers.

For each finger, the following will be presented :

- Two graphs comparing the coefficients of static friction (μ_{static}) measured thanks to the fits (k and n) for all the participants at the start and end of the experiment with a grip force (GF) of 5N : one for μ_{static} during **vertical movements** and one for μ_{static} during **horizontal movements**.
- A repeated measures ANOVA analysing the difference in μ_{static} between the start and end of the experiment for both **vertical** and **horizontal** movements.

A. Index

1. Graphs

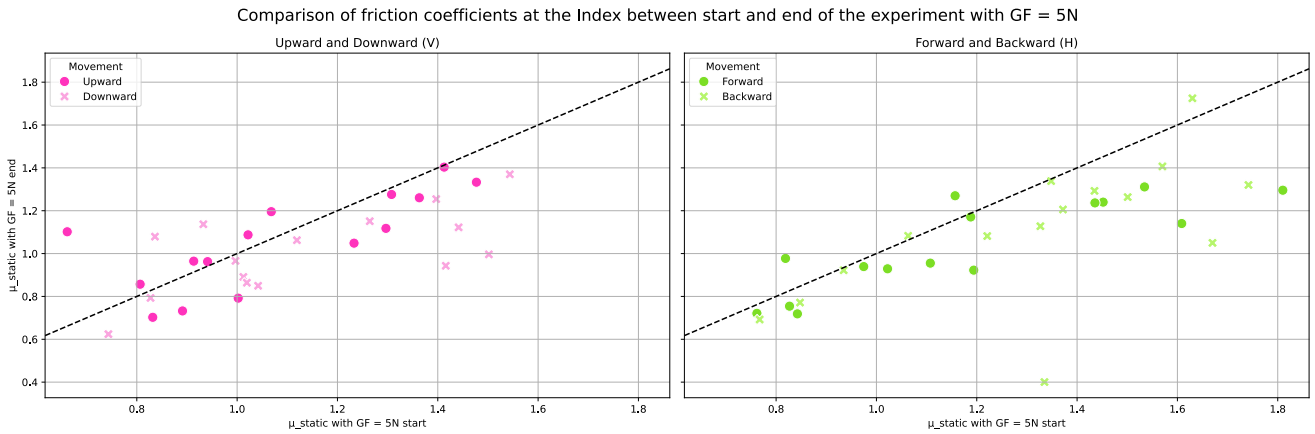


Figure 4.6: Comparision between μ_{static} start and end - Index

2. ANOVA

- With the index during **vertical movements** :

Source	F Value	Num DF	Den DF	Pr > F
Start vs end	4.54	1.0	14.0	0.0513

Table 4.3: Repeated measures ANOVA for the difference of μ_{static} between the start and the end with the index during V movements

The p-value (0.0513) exceeds 0.05 by a slight margin. This suggests a noticeable (but not statistically significant with 5%) trend between the friction coefficients at the start and end of the experiment. The graph shows that μ_{static} tends to decrease over the course of the experiment.

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- With the index during **horizontal movements** :

Source	F Value	Num DF	Den DF	Pr > F
Start vs end	9.7028	1.0	14.0	0.0076

Table 4.4: Repeated measures ANOVA for the difference of μ_{static} between the start and the end with the index during H movements

During horizontal movements, the p-value (0.0076) is less than 0.05, indicating a statistically significant difference between the μ_{static} at the start and end of the experiment. The graph demonstrates that μ_{static} tends to decrease over the course of the experiment, similar to the trend observed during vertical movements.

B. Thumb

1. Graphs

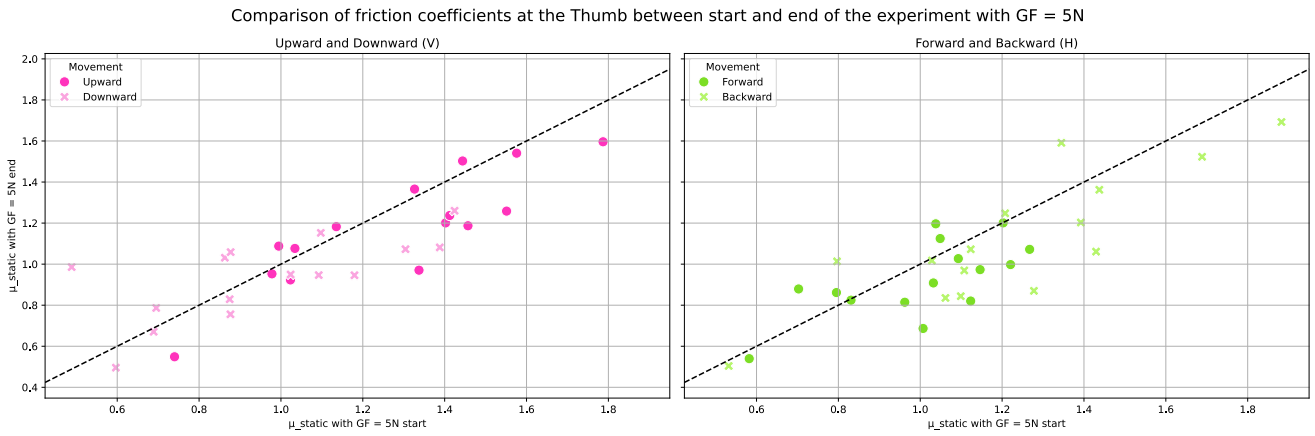


Figure 4.7: Comparision between μ_{static} start and end - Thumb

2. ANOVA

- With the thumb during **vertical movements** :

Source	F Value	Num DF	Den DF	Pr > F
Start vs end	0.7436	1.0	14.0	0.4031

Table 4.5: Repeated measures ANOVA for the difference of μ_{static} between the start and the end with the thumb during V movements

The p-value (0.4031) is larger than 0.05 indicating no statistically significant difference between the μ_{static} during the experiment.

- With the thumb during **horizontal movements** :

Source	F Value	Num DF	Den DF	Pr > F
Start vs end	6.2646	1.0	14.0	0.0253

Table 4.6: Repeated measures ANOVA for the difference of μ_{static} between the start and the end with the thumb during H movements

The p-value (0.0253) is smaller than 0.05, indicating a statistically significant difference between the μ_{static} at the start and end of the experiment. The graph demonstrates that μ_{static} tends to decrease over the course of the experiment, similar to the trends observed with the index.

4.3.3 Anisotropy

Secondly, it is worth considering whether the coefficient of friction is anisotropic. If a certain degree of anisotropy is detected, it could impact the analysis of variations in load force and grip force.

Here, the coefficient has been averaged between the beginning and the end to make the results easier to interpret.

A. Index

1. Graph

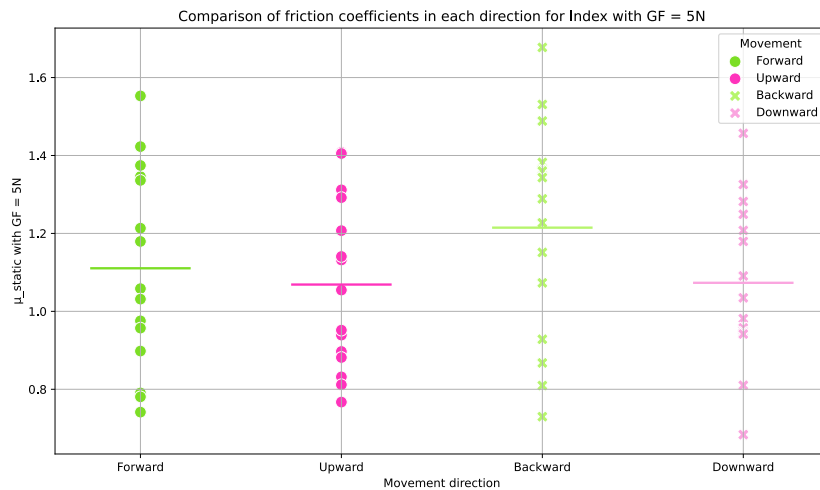


Figure 4.8: Comparison between μ_{static} for the 4 directions - Index

2. ANOVA anisotropy

Source	F Value	Num DF	Den DF	Pr > F
Movement	5.1512	3.0	42.0	0.0040

Table 4.7: Repeated measures ANOVA for the anisotropy of the μ_{static} - Index

The p-value (0.0040) is smaller than 0.05, indicating a significant difference between the four directions. Therefore, the μ_{static} is anisotropic for the index.

The μ_{static} is highest in the backward direction, followed by forward, downward and then upward.

3. T-tests anisotropy between in each direction

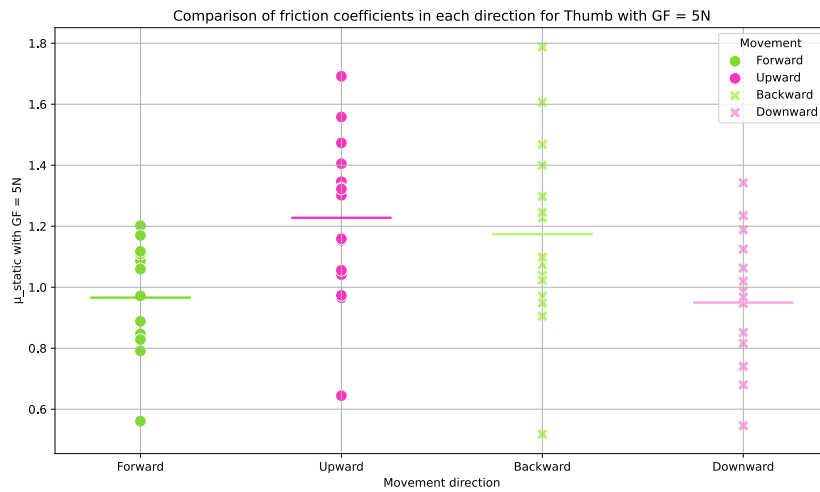
Comparison	t-stat	p-value
Forward vs Backward	-1.9182	0.0757
Upward vs Downward	-0.1379	0.8923

Table 4.8: T-tests difference between 2 movements of a same direction - Index

Neither of the two p-values is smaller than 0.025, which means that there is no significant difference between the coefficients of friction exerted in the 2 movements in the same direction.

B. Thumb

1. Graph

Figure 4.9: Comparison between μ_{static} for the 4 directions - Thumb

2. ANOVA anisotropy

Source	F Value	Num DF	Den DF	Pr > F
Movement	20.1279	3.0	42.0	3.066e-08

Table 4.9: Repeated measures ANOVA for the anisotropy of the μ_{static} - Thumb

The p-value (3.066e-08) is smaller than 0.05, indicating a significant difference between the four directions. Therefore, the μ_{static} is anisotropic for the thumb.

The μ_{static} is highest in the upward direction, followed by backward, forward and then downward.

3. T-tests anisotropy between in each direction

The two p-values are smaller than 0.025, which means that there is a significant difference between the coefficients of friction exerted in the 2 movements in the same direction, for the 2 sets of directions.

Comparison	t-stat	p-value
Forward vs Backward	-4.3538	0.0006
Upward vs Downward	6.2848	2.006e-05

Table 4.10: T-tests difference between 2 movements of a same direction - Thumb

4.4 Global analysis

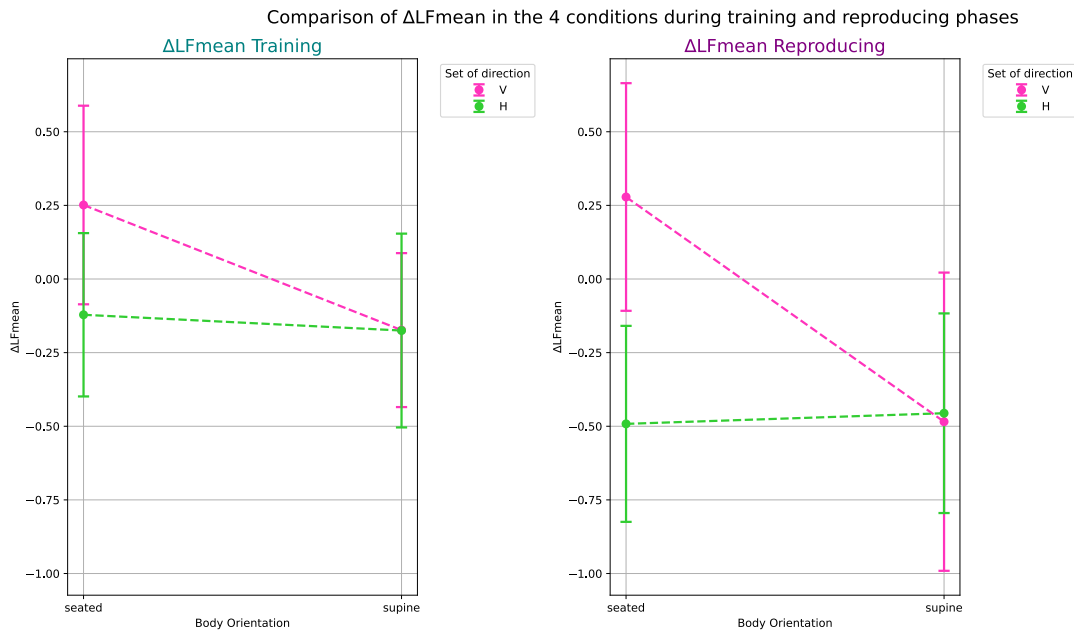
In order to provide an overview of the results, overall average graphs for both forces, their ratio and the safety margin are shown below with the comparison of **training** and **reproducing** phases in the four conditions. The graphs are generated using the overall averages and 95% confidence intervals are included. This indicates that 95% of the confidence intervals from each "experiment" should contain the true mean value. If these intervals include 0, it means that the variable is not significantly different from 0. Conversely, if the intervals do not include 0, then the variable is significantly different from 0. The t-test results presented for each condition in the next section are therefore already reflected in the graphs below.

An ANOVA is also performed for each value to examine the impact of the body orientation, the direction of the isometric forces and their interaction on it.

In addition, a t-test is carried out to test the significance of the difference between seated and supine, for both directions in reproducing phase.

4.4.1 $\Delta LFmean$

A. Global graphs

Figure 4.10: Comparison of $\Delta LFmean$ between training and reproducing phases in the 4 conditions

B. ANOVA

- In training :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	5.9321	1.0	14.0	0.0288
Set of direction	1.9841	1.0	14.0	0.1808
Body orientation:Set of direction	3.0469	1.0	14.0	0.1028

Table 4.11: Repeated measures ANOVA for ΔLF_{mean} in training phase

- Body orientation: The p-value (0.0288) is smaller than 0.05, suggesting that the body orientation has a significant impact on ΔLF_{mean} during training phase.

- In reproducing :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	6.2963	1.0	14.0	0.0250
Set of direction	4.2434	1.0	14.0	0.0585
Body orientation:Set of direction	11.8250	1.0	14.0	0.0040

Table 4.12: Repeated measures ANOVA for ΔLF_{mean} in reproducing phase

- Body orientation : the p-value (0.0250) is smaller than 0.05 meaning that the orientation of the body has an impact of ΔLF_{mean} during reproducing phase.
- Set of direction : the p-value (0.0585) is not smaller than 0.05 but is really close to it, meaning that the set of direction tends to have an impact on ΔLF_{mean} during reproducing phase.
- Body orientation:Set of direction : the p-value (0.004) is smaller than 0.05 meaning that the interaction between the body orientation and the set of direction significantly impacts ΔLF_{mean} during reproducing phase.

- Training vs reproducing with upward and downward isometric forces :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	17.3439	1.0	14.0	0.0009
State	2.6924	1.0	14.0	0.1231
Body orientation:State	6.3630	1.0	14.0	0.0243

Table 4.13: Repeated measures ANOVA for ΔLF_{mean} training vs reproducing in vertical movements

- Body orientation : the p-value (0.0009) is smaller than 0.05 meaning that body orientation has a significant impact on ΔLF_{mean} during vertical movements.
- Body orientation:State : the p-value (0.0243) is smaller than 0.05 meaning that the interaction between the body orientation and the state (training or reproducing) significantly impacts the ΔLF_{mean} during vertical movements.

- Training vs reproducing with forward and backward isometric forces :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	0.0037	1.0	14.0	0.9518
State	26.6704	1.0	14.0	0.0001
Body orientation:State	0.1876	1.0	14.0	0.6714

Table 4.14: Repeated measures ANOVA for ΔLF_{mean} training vs reproducing in horizontal movements

- State : the p-value (0.0001) is smaller than 0.05 meaning that the state has an impact on ΔLF_{mean} in horizontal movements.

C. T-tests seated vs supine in reproducing phase

- In vertical direction :

State	Set of direction	Force	T-statistic	P-value
Reproducing	V	Delta_LFmean	4.1209	0.0010

Table 4.15: T-tests ΔLF_{mean} seated vs supine in reproducing phase with vertical movements

The p-value (0.0010) is smaller than 0.05, meaning that there is a significant difference of ΔLF_{mean} between seated and supine in vertical direction.

- In horizontal direction :

State	Set of direction	Force	T-statistic	P-value
Reproducing	H	Delta_LFmean	-0.1942	0.8488

Table 4.16: T-tests ΔLF_{mean} seated vs supine in reproducing phase with horizontal movements

The p-value (0.8488) is larger than 0.05, meaning that there is not a significant difference of ΔLF_{mean} between seated and supine in horizontal direction.

4.4.2 ΔGF_{mean}

A. Global graphs

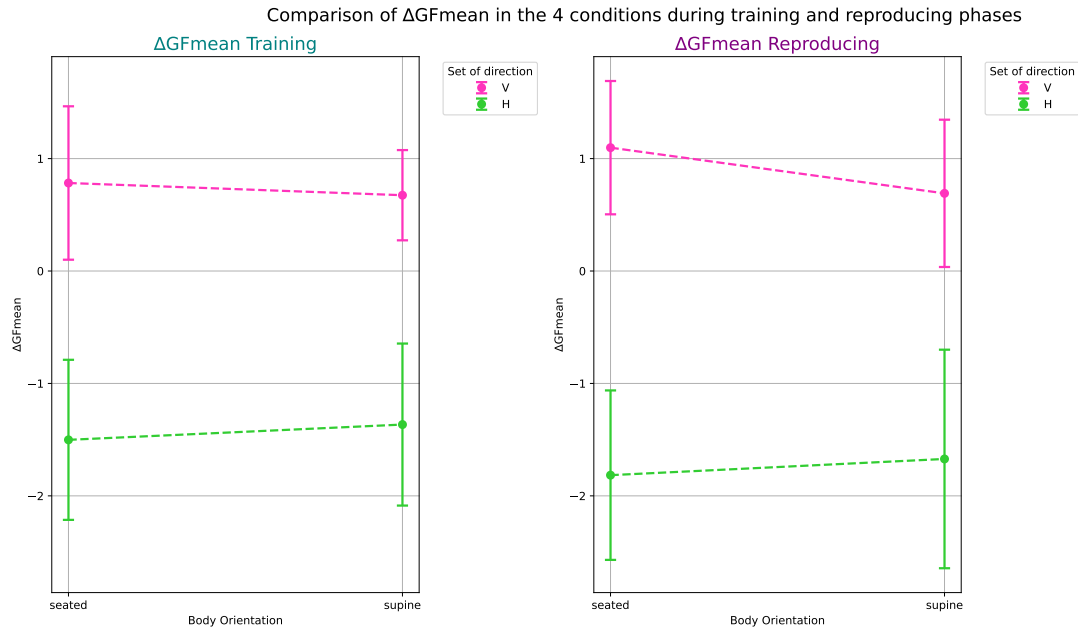


Figure 4.11: Comparison of ΔGF_{mean} between training and reproducing phases in the 4 conditions

B. ANOVA

• In training :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	0.0147	1.0	14.0	0.9051
Set of direction	18.0725	1.0	14.0	0.0008
Body orientation:Set of direction	0.5688	1.0	14.0	0.4632

Table 4.17: Repeated measures ANOVA for ΔGF_{mean} in training phase

- Set of direction : the p-value (0.0008) is smaller than 0.05, meaning that the set of direction significantly impacts ΔGF_{mean} during training phase.

• In reproducing :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	1.2454	1.0	14.0	0.2832
Set of direction	16.8223	1.0	14.0	0.0011
Body orientation:Set of direction	3.7783	1.0	14.0	0.0723

Table 4.18: Repeated measures ANOVA for ΔGF_{mean} in reproducing phase

- Set of direction : the p-value (0.0011) is smaller than 0.05, meaning that the set of direction significantly impacts ΔGF_{mean} during reproducing phase.

- Training vs reproducing with upward and downward isometric forces :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	2.5416	1.0	14.0	0.1331
State	1.7997	1.0	14.0	0.2011
Body orientation:State	1.4640	1.0	14.0	0.2463

Table 4.19: Repeated measures ANOVA for ΔGF_{mean} training vs reproducing in vertical movements

- None of the the p-value is smaller than 0.05 meaning that neither body orientation, state, nor their interaction has a significant impact on ΔGF_{mean} during vertical movements.

- Training vs reproducing with forward and backward isometric forces :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	0.8745	1.0	14.0	0.3655
State	10.4138	1.0	14.0	0.0061
Body orientation:State	0.00179	1.0	14.0	0.9668

Table 4.20: Repeated measures ANOVA for ΔGF_{mean} training vs reproducing in horizontal movements

- State : the p-value (0.0061) is smaller than 0.05 meaning that the state has an impact on ΔGF_{mean} in horizontal movements.

C. T-tests seated vs supine in reproducing phase

- In vertical direction :

State	Set of direction	Force	T-statistic	P-value
Reproducing	V	Delta_GFmean	2.5010	0.0254

Table 4.21: T-tests for ΔGF_{mean} seated vs supine in reproducing phase with vertical movements

The p-value (0.0254) is smaller than 0.05, meaning that there is a significant difference of ΔGF_{mean} between seated and supine in vertical direction.

- In horizontal direction :

State	Set of direction	Force	T-statistic	P-value
Reproducing	H	Delta_GFmean	-0.7087	0.4901

Table 4.22: T-tests for ΔGF_{mean} seated vs supine in reproducing phase with horizontal movements

The p-value (0.4901) is larger than 0.05, meaning that there is not a significant difference of ΔGF_{mean} between seated and supine in horizontal direction.

4.4.3 $\Delta\text{GFLF_ratio}$

A. Global graphs

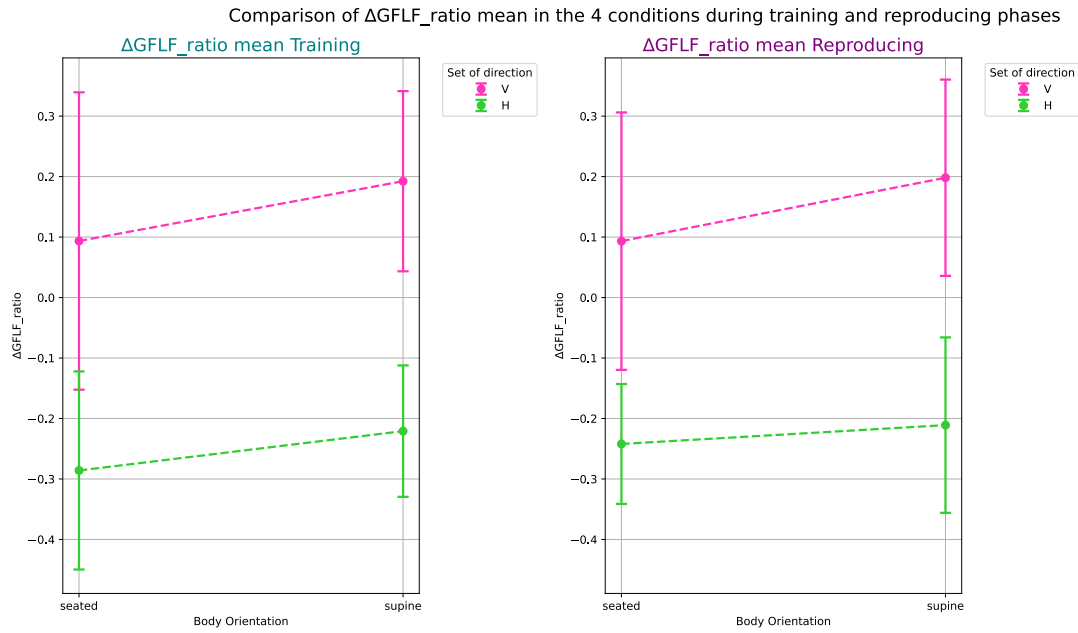


Figure 4.12: Comparison of $\Delta\text{GFLF_ratio}$ between training and reproducing phases in the 4 conditions

B. ANOVA

- In training :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	3.9482	1.0	14.0	0.0668
Set of direction	10.8584	1.0	14.0	0.0053
Body orientation:Set of direction	0.1041	1.0	14.0	0.7517

Table 4.23: Repeated measures ANOVA for $\Delta\text{GFLF_ratio}$ in training phase

- Set of direction : the p-value (0.0053) is smaller than 0.05, meaning that the set of direction significantly impacts the $\Delta\frac{GF}{LF}$ mean during the training phase.

- In reproducing :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	1.7089	1.0	14.0	0.2122
Set of direction	11.4014	1.0	14.0	0.0045
Body orientation:Set of direction	0.9819	1.0	14.0	0.3386

Table 4.24: Repeated measures ANOVA for $\Delta\text{GFLF_ratio}$ in reproducing phase

- Set of direction : again, the p-value (0.0045) is smaller than 0.05, meaning that the set of direction significantly impacts the $\Delta\frac{GF}{LF}$ mean during the reproducing phase.

- Training vs reproducing with upward and downward isometric forces :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	1.7105	1.0	14.0	0.2119
State	0.0241	1.0	14.0	0.8787
Body orientation:State	0.0255	1.0	14.0	0.87539

Table 4.25: Repeated measures ANOVA for $\Delta\text{GFLF_ratio}$ training vs reproducing in vertical movements

- None of the the p-value is smaller than 0.05 meaning that neither body orientation, state, nor their interaction has a significant impact on $\Delta\text{GFLF_ratio}$ during vertical movements.

- Training vs reproducing with forward and backward isometric forces :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	3.1422	1.0	14.0	0.0980
State	1.3290	1.0	14.0	0.2683
Body orientation:State	0.2081	1.0	14.0	0.6552

Table 4.26: Repeated measures ANOVA for $\Delta\text{GFLF_ratio}$ training vs reproducing in horizontal movements

- Again, none of the the p-value is smaller than 0.05 meaning that neither body orientation, state, nor their interaction has a significant impact on $\Delta\text{GFLF_ratio}$ during horizontal movements.

C. T-tests seated vs supine

- In vertical direction :

State	Set of direction	Force	T-statistic	P-value
Reproducing	V	Delta_GFLF_ratio	-1.3262	0.2060

Table 4.27: T-tests for $\Delta\text{GFLF_ratio}$ seated vs supine in reproducing phase with vertical movements

The p-value (0.2060) is larger than 0.05, meaning that there is not a significant difference of $\Delta\frac{GF}{LF}$ mean between seated and supine in vertical direction.

- In horizontal direction :

State	Set of direction	Force	T-statistic	P-value
Reproducing	H	Delta_GFLF_ratio	-0.7094	0.4897

Table 4.28: T-tests for $\Delta\text{GFLF_ratio}$ seated vs supine in reproducing phase with horizontal movements

The p-value (0.4897) is larger than 0.05, meaning that there is not a significant difference of $\Delta\frac{GF}{LF}$ between seated and supine in horizontal direction.

4.4.4 Δ Safety margin

The safety margin is calculated using the slip force for each finger, with the smallest value being selected, as explained in Chapter 3.

Two of the four repeated-measures ANOVAs of the subsection 4.3.2 showed a significant difference between the coefficients of friction at the start and end of the experiment and one indicated a significant trend. Therefore, the following approach was adopted:

- The coefficients at the start of the experiment were used to calculate the safety margin for the trials of the first condition performed.
- The coefficients at the end of the experiment were used to calculate the safety margin for the trials of the last condition performed.
- An average of the coefficients at the beginning and end was used to calculate the safety margin for the trials of the middle conditions (the second and third).

This technique therefore allows the safety margin to take into account the difference between the μ_{static} at the beginning and at the end, calculating it as closely as possible to reality.

In addition, as anisotropy in the μ_{static} was observed in 3 of the 4 cases tested in the subsection 4.3.3, the μ_{static} was calculated using the fits specific to the direction of movement on the plateau in order to incorporate this anisotropy and calculate the safety margin even more realistically.

A. Global graphs

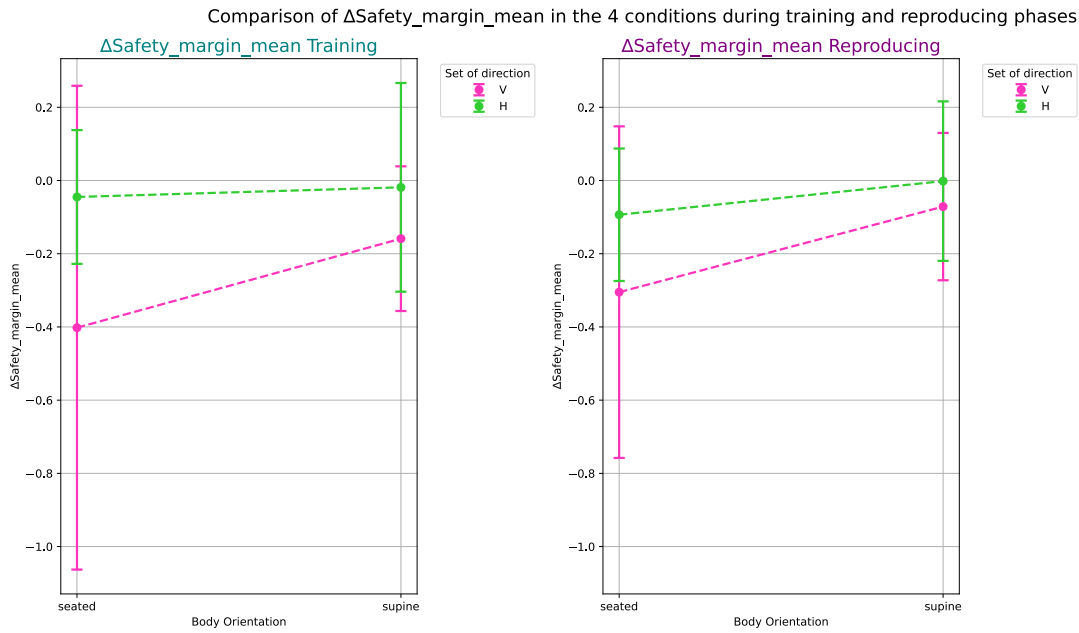


Figure 4.13: Comparison of Δ Safety_margin_mean between training and reproducing phases in the 4 conditions

B. ANOVA

- In training :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	0.5378	1.0	14.0	0.4755
Set of direction	2.7303	1.0	14.0	0.1207
Body orientation:Set of direction	0.6668	1.0	14.0	0.4279

Table 4.29: Repeated measures ANOVA for Δ Safety_margin_mean in training phase

- None of the p-values is smaller than 0.05, meaning that neither the body orientation, nor the set of direction, nor the interaction between the two had any impact on the Δ Safety margin mean during the training phase.

- In reproducing :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	1.7089	1.0	14.0	0.2122
Set of direction	11.4014	1.0	14.0	0.0045
Body orientation:Set of direction	0.9819	1.0	14.0	0.3386

Table 4.30: Repeated measures ANOVA for Δ Safety_margin_mean in reproducing phase

- Set of direction : the p-value (0.0045) is smaller than 0.05 indicating that the set of direction significantly impacts the Δ Safety margin mean during the reproducing phase.

- Training vs reproducing with upward and downward isometric forces :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	0.8829	1.0	14.0	0.3633
State	2.5357	1.0	14.0	0.1336
Body orientation:State	0.0064	1.0	14.0	0.9374

Table 4.31: Repeated measures ANOVA for Δ Safety margin training vs reproducing in vertical movements

- None of the the p-value is smaller than 0.05 meaning that neither body orientation, state, nor their interaction has a significant impact on Δ Safety margin during vertical movements.

- Training vs reproducing with forward and backward isometric forces :

Source	F Value	Num DF	Den DF	Pr > F
Body orientation	1.0603	1.0	14.0	0.3206
State	0.1169	1.0	14.0	0.7374
Body orientation:State	0.4201	1.0	14.0	0.5274

Table 4.32: Repeated measures ANOVA for Δ Safety margin training vs reproducing in horizontal movements

- Again, none of the the p-value is smaller than 0.05 meaning that neither body orientation, state, nor their interaction has a significant impact on Δ Safety margin during **horizontal movements**.

C. T-tests seated vs supine

- **In vertical direction :**

State	Set of direction	Force	T-statistic	P-value
Reproducing	V	Delta.Safety_margin_tot	-1.0993	0.2902

Table 4.33: T-tests for Δ Safety margin seated vs supine in reproducing phase with vertical movements

The p-value (0.2902) is larger than 0.05, meaning that there is not a significant difference of Δ Safety margin between seated and supine in **vertical direction**.

- **In horizontal direction :**

State	Set of direction	Force	T-statistic	P-value
Reproducing	H	Delta.Safety_margin_tot	1.4248	0.1761

Table 4.34: T-tests for Δ Safety margin seated vs supine in reproducing phase with horizontal movements

The p-value (0.1761) is larger than 0.05, meaning that there is not a significant difference of Δ Safety margin between seated and supine in **horizontal direction**.

4.5 Detailed analysis

In this section, a more detailed analysis of these variations will be presented for each condition.

For each of the four conditions, different results are shown :

- **Detailed graphs:** These graphs feature the x-axis representing the two directions of the set and the y-axis representing either the force applied on the manipulandum, the ratio of the two forces or the safety margin. Two distinct colours differentiate the **training** and **reproducing** phases. The graphs display the results for each participant as well as the average results across all participants, with the average results shown in darker colours.
- **Boxplot graphs:** These graphs illustrate the average difference (Δ) between the two movement directions for each subject and the standard deviation of these forces. They also show the difference in the ratio $\frac{GF}{LF}$ and in the safety margin between the two directions.
- **Significance to 0:** These results present a T-test conducted on $\Delta LFmean$ and $\Delta GFmean$ to determine the significance of the results being zero for both the **training** and **reproducing** phases.

4.5.1 Seated with upward and downward isometric forces

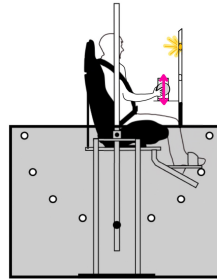


Figure 4.14: Seated with upward and downward isometric forces

A. Detailed graphs

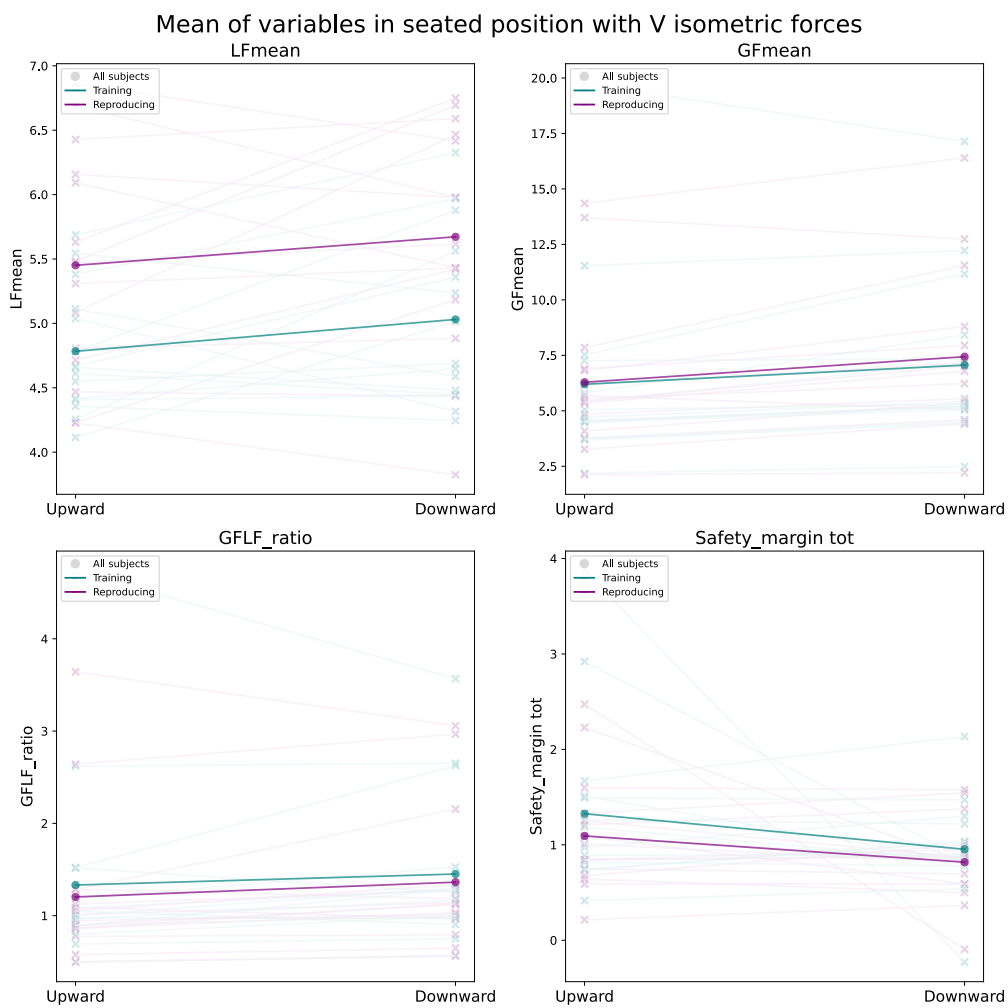


Figure 4.15: Detailed graphs in seated position with upward and downward isometric forces

- **LFmean** : the **reproducing phase** shows a larger LFmean than the **training phase** for both upward and downward movements, with the difference remaining approximately the same. For both phases, LFmeans are larger during downward movements.
- **GFmean** : the **reproducing phase** during upward movements shows a slightly larger GFmean than in the **training phase**, though the difference is minimal. A larger difference between the two phases can be seen for downward movements. For both phases, GFmeans are larger during downward movements.
- **$\frac{GF}{LF}$ ratio** : the **training phase** shows a bigger ratio for both upward and downward movements. With the exception of a few subjects, most individual ratios lie under approximately 1.3.
- **Safety margin** : the **training phase** shows a bigger safety margin for both upward and downward movements. The safety margin is smaller in downward movements.

B. Boxplot graphs

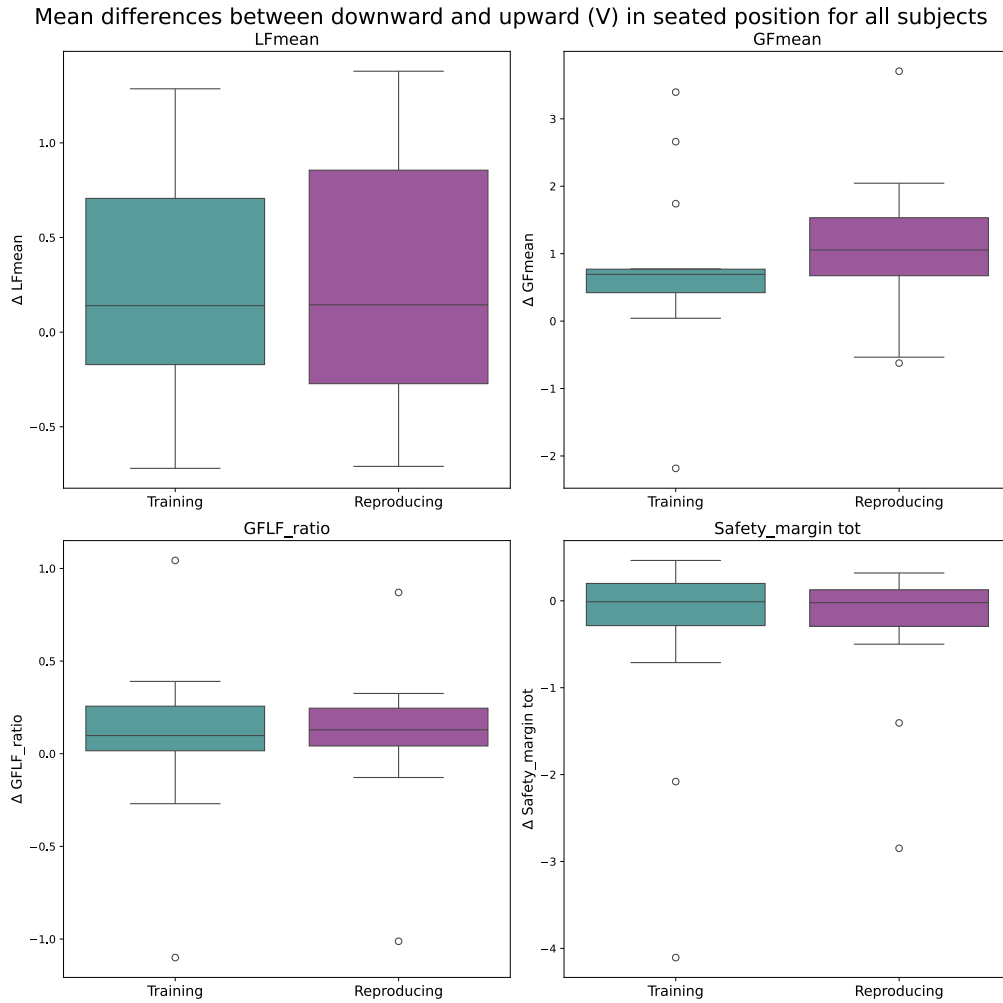


Figure 4.16: Boxplot graphs in seated position with upward and downward isometric forces

- ΔLFmean : there is not a real difference in the median of the ΔLFmean between **training** and **reproducing** phases.
- ΔGFmean : the median in the **reproducing phase** is larger than the one in the **training phase** and its whiskers are bigger. However, there are some outliers in the **training phase**.
- $\Delta \frac{\text{GF}}{\text{LF}}$ ratio : the medians are similar and close to zero.
- $\Delta \text{Safety margin}$: the medians are similar and almost equal to zero.

C. Significance to 0

The t-tests carried out in this condition (seated - upward and downward isometric forces) show these results :

- **In training :**

State	Body orientation	Set of direction	Variable	Delta Mean	Standard Deviation	t-statistic	p-value
Training	seated	V	LFmean	0.2513	0.6088	1.5986	0.1322
Training	seated	V	GFmean	0.7829	1.2322	2.4607	0.0275

Table 4.35: Results of the t-test in seated V for training phase

Thus, ΔGFmean is significantly different from 0 during training phase.

- **In reproducing :**

State	Body orientation	Set of direction	Variable	Delta Mean	Standard Deviation	t-statistic	p-value
Reproducing	seated	V	LFmean	0.2785	0.6979	1.5454	0.1446
Reproducing	seated	V	GFmean	1.0973	1.0707	3.9692	0.0014

Table 4.36: Results of the t-test in seated V for reproducing phase

Thus, ΔGFmean is also significantly different from 0 during reproducing phase.

4.5.2 Seated with forward and backward isometric forces

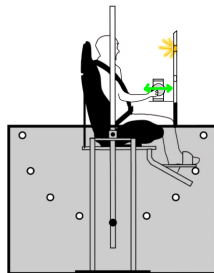


Figure 4.17: Seated with forward and backward isometric forces

A. Detailed graphs

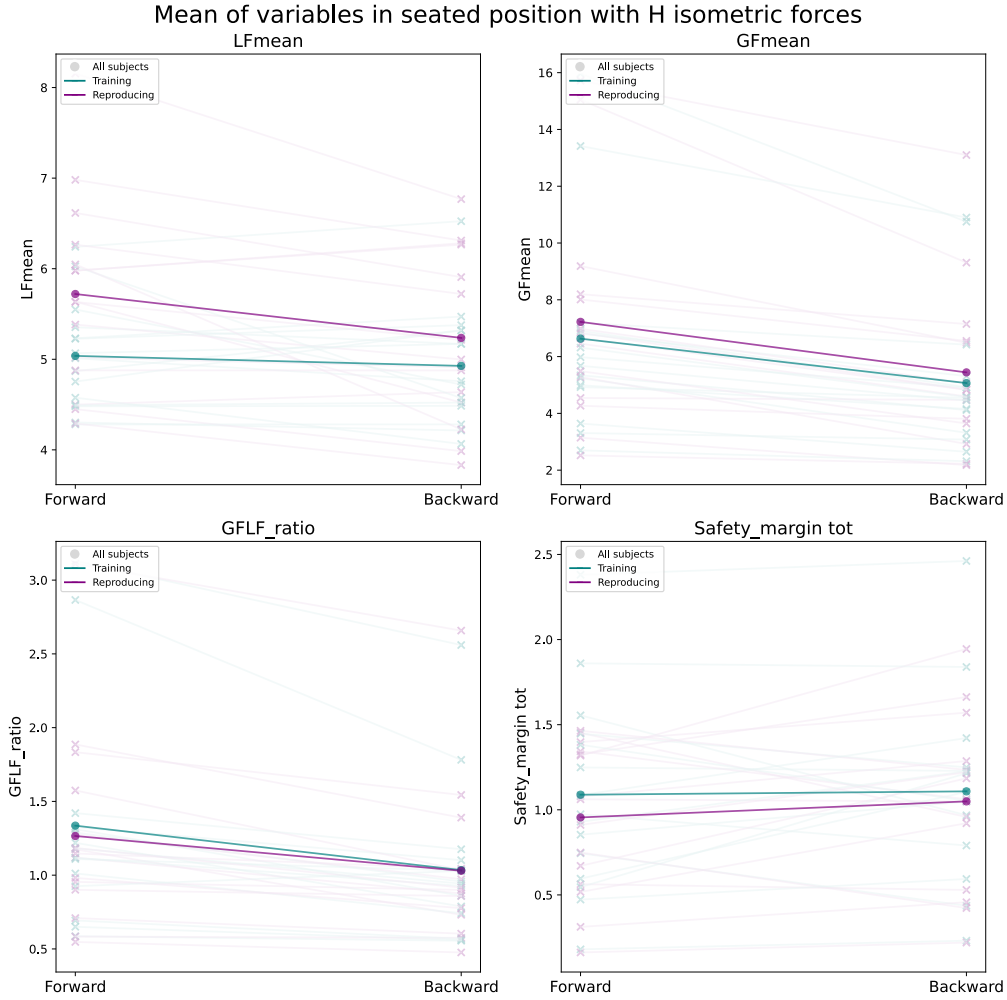


Figure 4.18: Detailed graphs in seated position with forward and backward isometric forces

- **LFmean** : the **reproducing phase** shows a larger LFmean than the **training phase** for both upward and downward movements, with a bigger difference during forward movements. For the **training phase**, the LFmean is really similar for forward and backward movements. For the **reproducing phase**, the LFmean decreases in backward movements.
- **GFmean** : the **reproducing phase** during both movements shows a slightly larger GFmean than in the **training phase**. During both phases, GFmeans are larger in forward movements.
- **$\frac{GF}{LF}$ ratio** : during backward movements both ratios are almost equal. During forward movements, they are slightly bigger but remain almost the same. With the exception of a few subjects, most individual ratios lie under approximately 1.3.
- **Safety margin** : the **training phase** shows a bigger safety margin for both upward and downward movements. The safety margin is slightly larger in backward movements.

B. Boxplot graphs

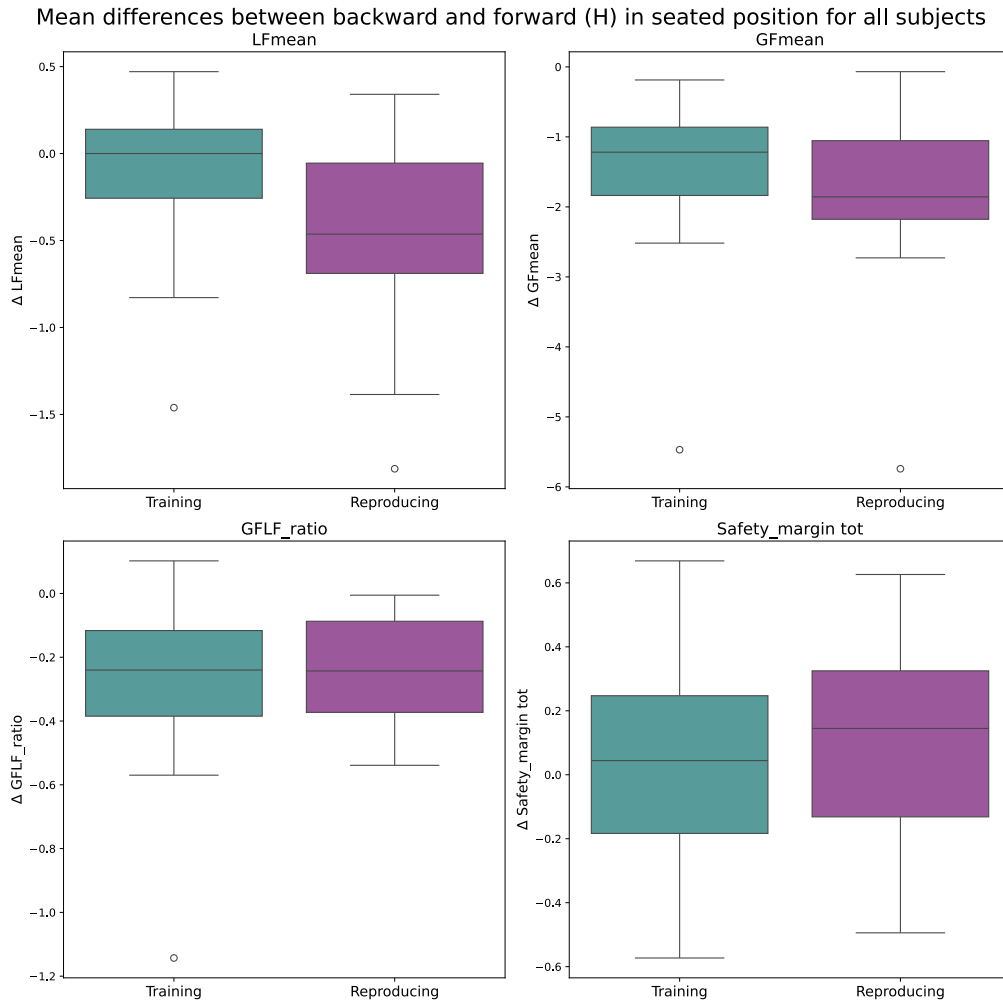


Figure 4.19: Boxplot graphs in seated position with forward and backward isometric forces

- **ΔLFmean** : the median during the **training** is close to zero meaning that LFmean during forward and backward movements are really similar. However, the median during the **reproducing phase** is close to -0.5 .
- **ΔGFmean** : both medians are negative.
- **$\Delta\frac{\text{GF}}{\text{LF}}$ ratio** : as the difference in ΔLFmean between **training** and **reproducing** is similar to the difference in ΔGFmean , the ratios are really similar in both phases.
- **$\Delta\text{Safety margin}$** : for both phases, the variability is quite high. The median during **reproducing** is larger than the one during **training phase**.

C. Significance to 0

The t-tests carried out in this condition (seated - forward and backward isometric forces) show these results :

- In training :

State	Body orientation	Set of direction	Variable	Delta Mean	Standard Deviation	t-statistic	p-value
Training	seated	H	LFmean	-0.1215	0.5007	-0.9395	0.3634
Training	seated	H	GFmean	-1.5017	1.2856	-4.5239	0.0005

Table 4.37: Results of the t-test in seated H for training phase

The $\Delta GFmean$ is significantly different from 0 during training phase.

- In reproducing :

State	Body orientation	Set of direction	Variable	Delta Mean	Standard Deviation	t-statistic	p-value
Reproducing	seated	H	LFmean	-0.4919	0.6008	-3.1707	0.0068
Reproducing	seated	H	GFmean	-1.8159	1.361	-5.1674	0.0001

Table 4.38: Results of the t-test in seated H for reproducing phase

Thus, $\Delta LFmean$ and $\Delta GFmean$ are significantly different from 0 during reproducing phase.

4.5.3 Supine with upward and downward isometric forces

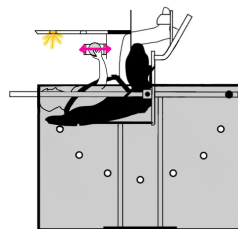


Figure 4.20: Supine with upward and downward isometric forces

A. Detailed graphs

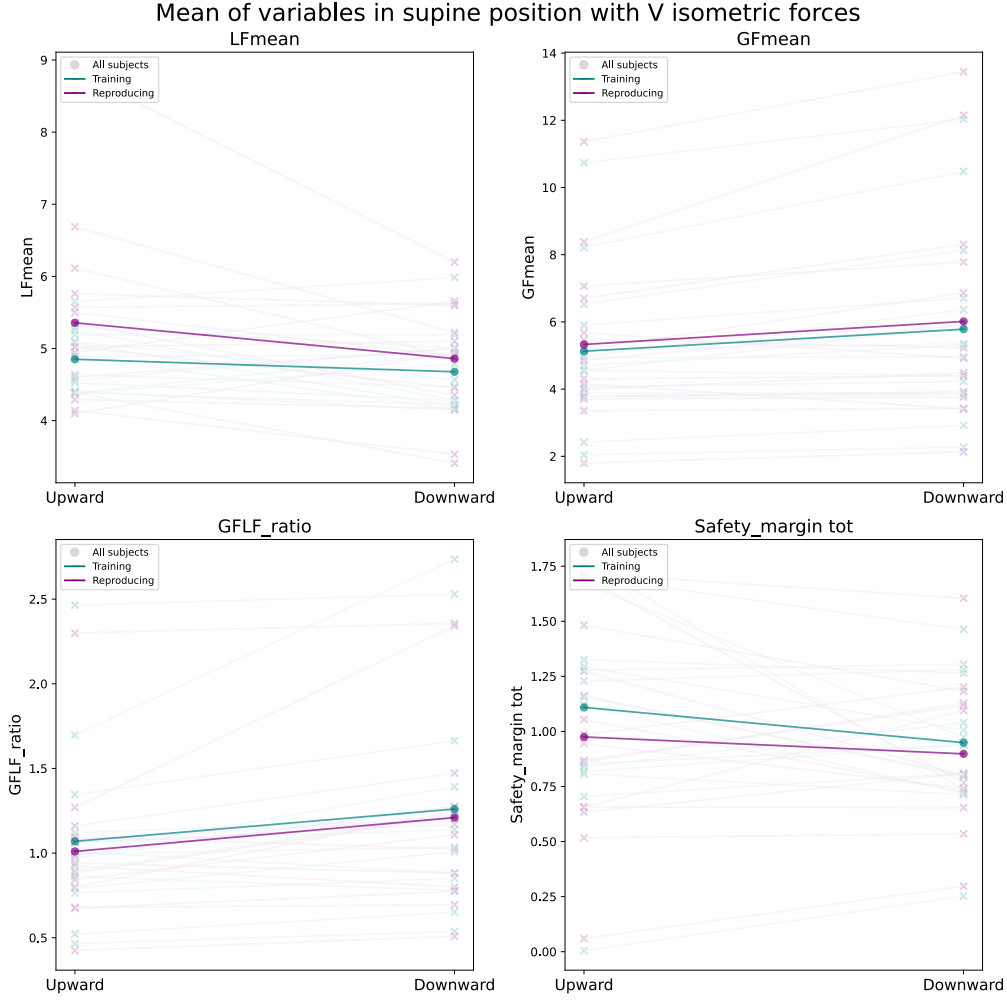


Figure 4.21: Detailed graphs in supine position with upward and downward isometric forces

- **LFmean** : the difference in LFmean between **training** and **reproducing** is bigger during upward movements than downward ones. Additionally, the LFmeans during **training phase** are almost equal in upward and downward movements. In contrast, GFmean is smaller in downward movements during **reproducing phase**.
- **GFmean** : the GFmeans are slightly larger during **reproducing phase** but remains really close to each other. They are larger during downward movements.
- **$\frac{GF}{LF}$ ratio** : the ratios are larger in downward movements. With the exception of a few subjects, most individual ratios lie under approximately 1.2.
- **Safety margin** : the **training phase** shows a bigger safety margin for both upward and downward movements. The safety margin is smaller in downward movements.

B. Boxplot graphs

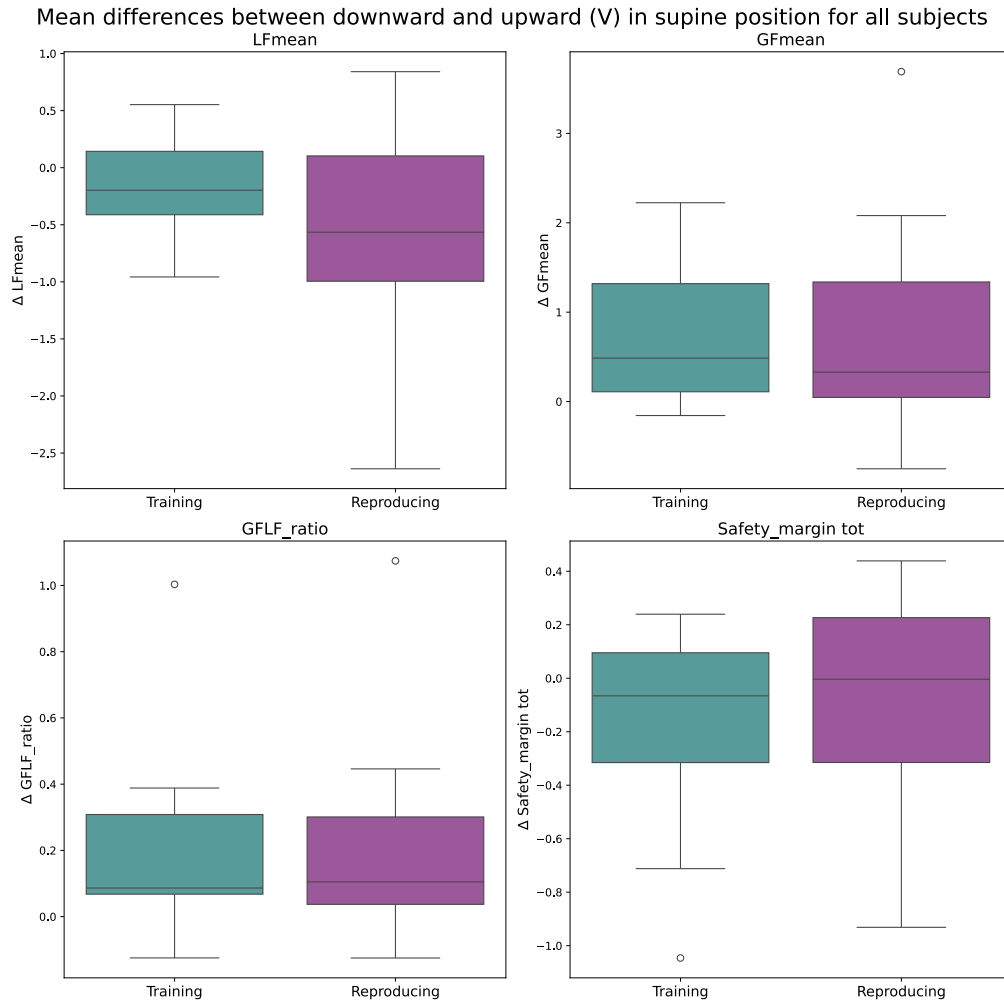


Figure 4.22: Boxplot graphs in supine position with upward and downward isometric forces

- ΔLFmean : both medians are negative. The boxplot during **reproducing phase** has bigger whiskers thus there is a wider range of differences.
- ΔGFmean : the medians are quite similar.
- $\Delta \frac{\text{GF}}{\text{LF}}$ ratio : both medians are approximately equals to 0.1.
- $\Delta \text{Safety margin}$: the median during **training phase** is negative. However, the median during **reproducing phase** is close to zero.

C. Significance to 0

The t-tests carried out in this condition (supine - upward and downward isometric forces) show these results :

- In training :

State	Body orientation	Set of direction	Variable	Delta Mean	Standard Deviation	t-statistic	p-value
Training	supine	V	LFmean	-0.1735	0.472	-1.4238	0.1764
Training	supine	V	GFmean	0.6743	0.7248	3.6035	0.0029

Table 4.39: Results of the t-test in supine V for training phase

Thus, $\Delta GFmean$ is significantly different from 0 during training phase.

- In reproducing :

State	Body orientation	Set of direction	Variable	Delta Mean	Standard Deviation	t-statistic	p-value
Reproducing	supine	V	LFmean	-0.4845	0.9142	-2.0525	0.0593
Reproducing	supine	V	GFmean	0.6908	1.183	2.2617	0.0402

Table 4.40: Results of the t-test in supine V for reproducing phase

Thus, $\Delta GFmean$ is also significantly different from 0 during reproducing phase.

4.5.4 Supine with forward and backward isometric forces

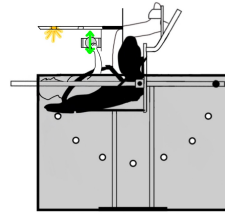


Figure 4.23: Supine with forward and backward isometric forces

A. Detailed graphs

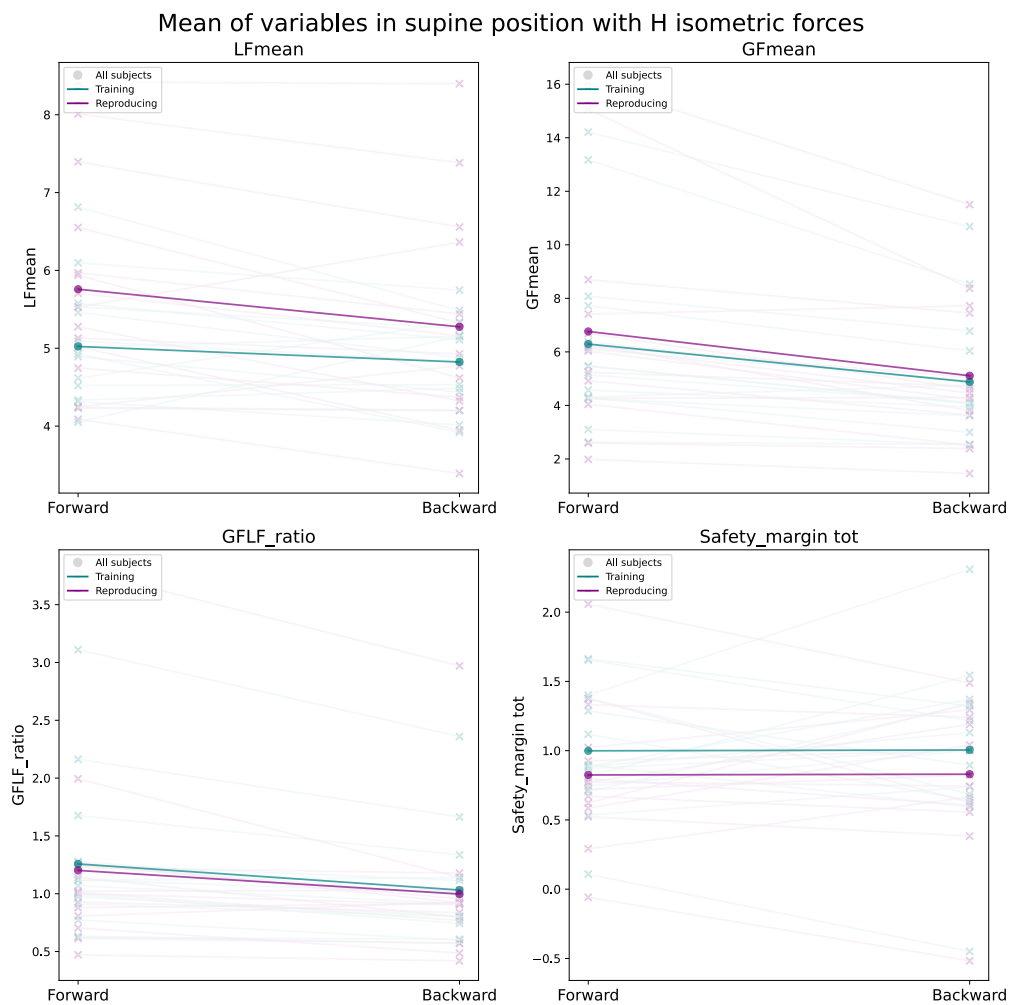


Figure 4.24: Detailed graphs in supine position with forward and backward isometric forces

- **LFmean** : as in every other conditions, LFmeans are larger during **reproducing phase**. Here, this difference is bigger during forward movements.

- **GFmean** : the GFmeans are slightly larger during **reproducing phase** but remains really close to each other. They are larger in forward movements during both phases.
- $\frac{GF}{LF}$ ratio : the ratios are larger in forward movements and are quite similar in both phases.
- **Safety margin** : the safety margin is larger during **training phase** in both movements. During both phases the safety margin is almost the same in forward and backward movements.

B. Boxplot graphs

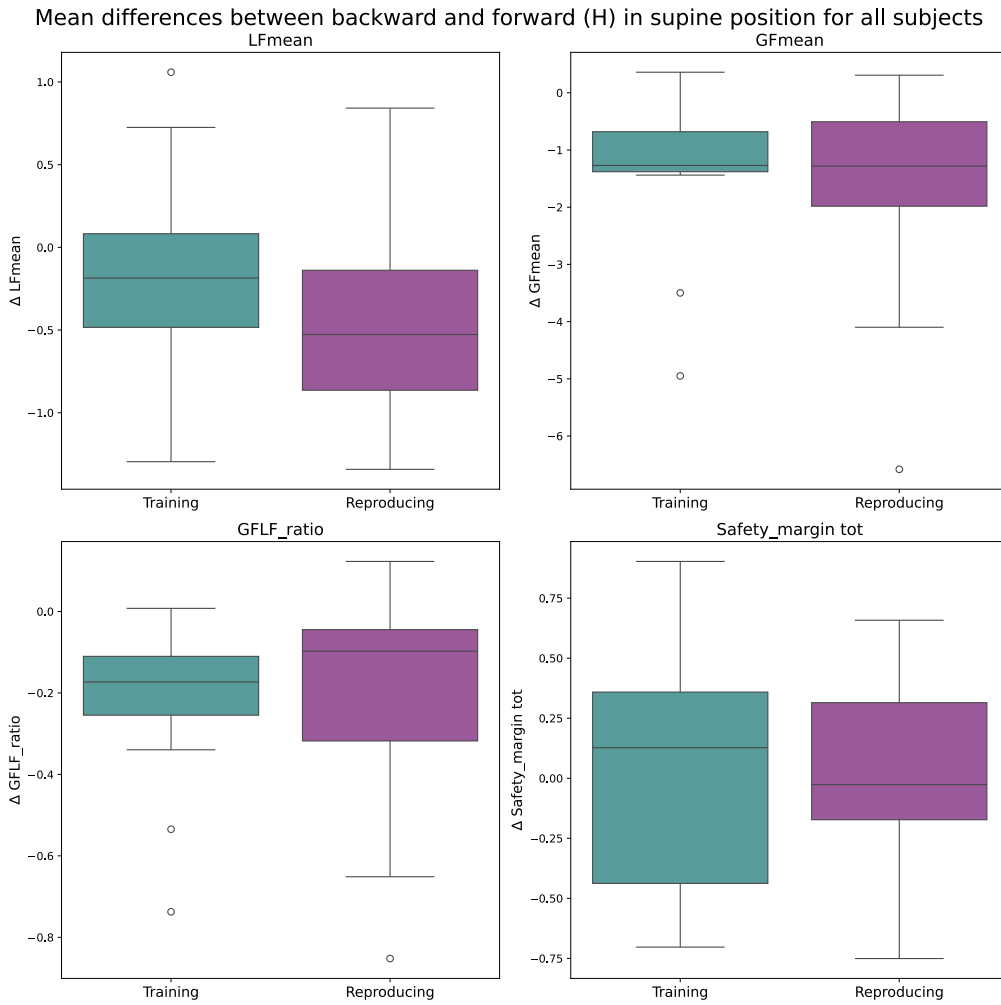


Figure 4.25: Boxplot graphs in supine position with forward and backward isometric forces

- $\Delta LFmean$: both medians are negative.
- $\Delta GFmean$: the medians are quite similar and both negative.
- $\Delta \frac{GF}{LF}$ ratio : the median during **reproducing phase** is larger.

- **Δ Safety margin** : the variability during **training phase** is quite high. The median during **reproducing phase** is close to zero.

C. Significance to 0

The t-tests carried out in this condition (supine - forward and backward isometric forces) show these results :

- **In training :**

State	Body orientation	Set of direction	Variable	Delta Mean	Standard Deviation	t-statistic	p-value
Training	supine	H	LFmean	-0.1749	0.5941	-1.1405	0.2732
Training	supine	H	GFmean	-1.3658	1.3012	-4.0652	0.0012

Table 4.41: Results of the t-test in supine H for training phase

Thus, Δ GFmean is significantly different from 0 during training phase.

- **In reproducing :**

State	Body orientation	Set of direction	Variable	Delta Mean	Standard Deviation	t-statistic	p-value
Reproducing	supine	H	LFmean	-0.4557	0.612	-2.884	0.012
Reproducing	supine	H	GFmean	-1.6718	1.7552	-3.6891	0.0024

Table 4.42: Results of the t-test in supine H for reproducing phase

Thus, Δ LFmean and Δ GFmean are significantly different from 0 during reproducing phase.

Chapter 5

Discussion

5.1 Expected results

As explained in Chapter 2, the sense of effort is influenced by gravity. Indeed, exerting a given force upward against gravity requires more effort than exerting the same force downward in the direction of gravity. Study [6] proposes the hypothesis that this sense of effort influences the perception of forces.

Under this hypothesis, forces exerted against gravity are perceived as greater due to the sense of effort. If participants perceive the isometric load forces exerted against gravity as greater than those exerted in the direction of gravity, the results during reproducing phase will show a lower load force in the opposite direction of gravity (since it is overestimated) and a higher load force in the same direction of gravity. However, study [6] showed that grip force does not vary with direction. The researchers hypothesized that the GF would represent what the subjects think they are doing. Since participants believe they are performing the task correctly by exerting the same forces in both directions, the difference of GF is equal to zero. This indicates that participants believe they are performing the task correctly, unaware (as the GF/LF ratio would remain constant if they were) that they are applying different load forces depending on the direction.

Moreover, during training, no asymmetry or effect from the conditions is expected since auditory feedback is present. However, a slight effect is possible because the feedback allows for a margin of error (4-6N).

Within this experiment, the expected results during reproducing phase under this hypothesis are supposed to be :

- **Seated with upward and downward isometric forces:** The isometric forces are exerted along the axis of gravity, so the upward load force is weaker than the downward load force. Therefore, the ΔLF is greater than 0 and the ΔGF is equal to 0.
- **Seated with forward and backward isometric forces:** The isometric forces are exerted along the axis perpendicular to gravity. Hence, the sense of effort is not affected by gravity and the load forces are perceived equally. Thus, both ΔLF and ΔGF are equal to 0.

- **Supine with upward and downward isometric forces:** The isometric forces are exerted along the axis perpendicular to gravity. Therefore, the sense of effort is not influenced by gravity and the load forces are expected to be equivalent in both directions. Thus, both ΔLF and ΔGF are equal to 0.
- **Supine with forward and backward isometric forces:** The isometric forces are exerted along the axis of gravity, so the upward load force is expected to be lower than the downward load force. Therefore, the ΔLF is greater than 0 and the ΔGF is equal to 0.

These expected results are presented on Figure 5.1.

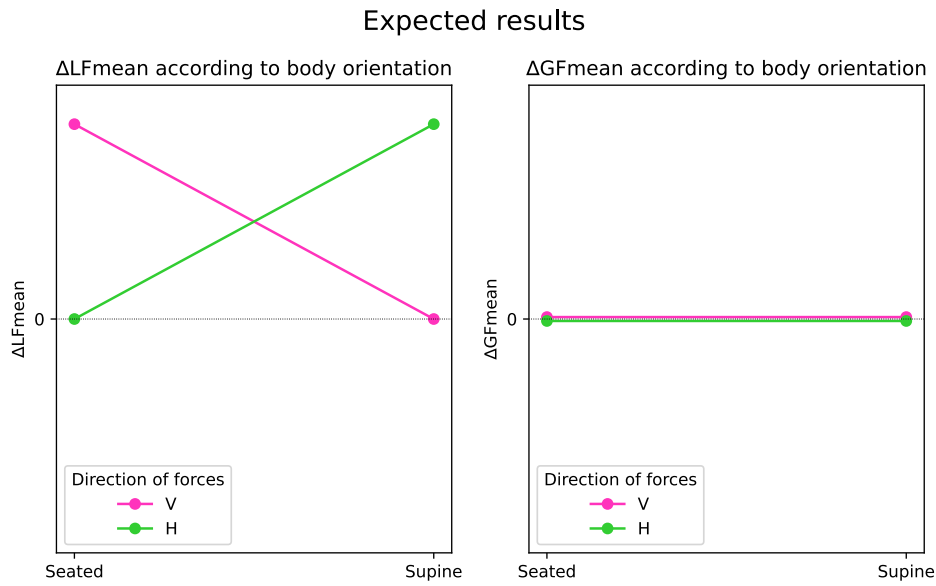


Figure 5.1: Expected results in reproducing phase

As shown on Figure 5.1, it was expected that the ΔLF_{mean} results between seated and supine within the same set of directions (V or H) are expected to be significantly different. Conversely, the ΔGF_{mean} results between seated and supine within the same set of directions (V or H) are not expected to be significantly different.

In addition, the ΔLF_{mean} for the upward and downward isometric forces would decrease (negative slope) between the seated and supine positions, and that the ΔLF_{mean} for the forward and backward isometric forces would increase (positive slope).

5.2 Observed results and hypotheses

The observed results were presented in Chapter 4.

- **Seated with upward and downward isometric forces:** ΔLF_{mean} is positive but not significantly different from 0. ΔGF_{mean} is positive and significantly different from 0. Therefore, the results are not consistent with the hypotheses.
- **Seated with forward and backward isometric forces:** ΔLF_{mean} is less than 0 and significantly different from 0. ΔGF_{mean} is negative and significantly different from 0. Therefore, the results are not consistent with the hypotheses.
- **Supine with upward and downward isometric forces:** ΔLF_{mean} is negative but not significantly different from 0. Its non significant difference from 0 is consistent with the hypotheses. ΔGF_{mean} is positive and significantly different from 0, which is not consistent with the hypotheses.
- **Supine with forward and backward isometric forces:** ΔLF_{mean} is negative and significantly different from 0. Its significant difference from 0 is consistent with the hypotheses. ΔGF_{mean} is negative and significantly different from 0, which is not consistent with the hypotheses.

These observed results are presented on Figure 5.2.

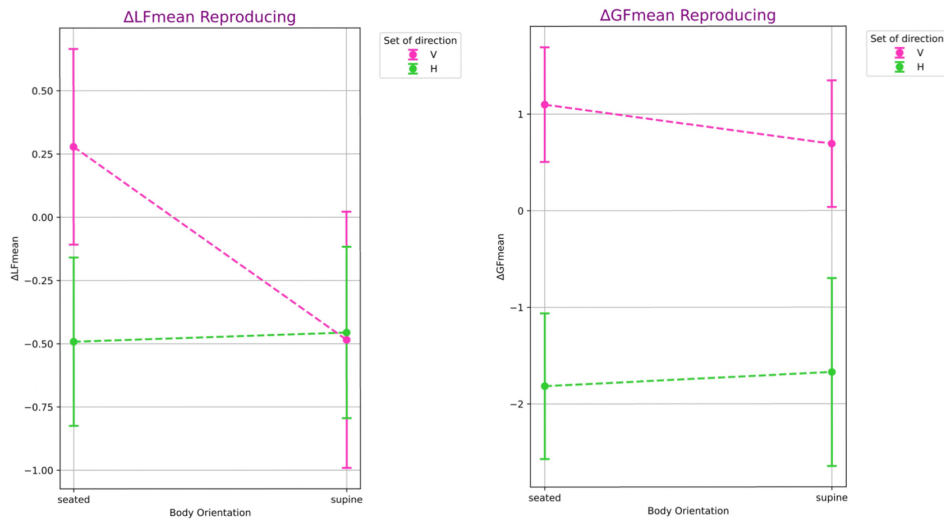


Figure 5.2: Observed results in reproducing phase

5.2.1 Global observations

The observed results show a significant difference in ΔLF_{mean} between seated and supine body orientations in **upward and downward isometric forces**, which is consistent with the hypothesis that the effort required to support the weight of the arm biases load force estimation. However, ΔGF_{mean} also shows a significant difference between the two body orientations, which is not in line with the hypothesis that GF should be proportional to the estimated LF, supposed to be constant in all conditions (since the participants are

supposed to think that they perform the same LF under all conditions).

Conversely, for the **forward and backward isometric forces**, ΔLF_{mean} is not significantly different between seated and supine, which is inconsistent with our hypotheses. However, ΔGF_{mean} is not significantly different between seated and supine, which is consistent with the hypotheses.

Many of the observed results do not align with the hypothesis presented in article [6]. Nevertheless, we can observe that the slopes trends of the ΔLF_{mean} are consistent with these hypotheses. Specifically, the slope of ΔLF_{mean} between seated and supine for **upward and downward isometric forces** is negative (meaning that ΔLF_{mean} decreases), while the slope of ΔLF_{mean} between seated and supine for **forward and backward isometric forces** is (slightly) positive (meaning that ΔLF_{mean} increases).

The results also indicate for ΔLF_{mean} a significant interaction between body orientation and the set of directions. This interaction means that when the chair is rotated, the influence of force direction changes. Thus, when in seated or supine positions, the direction of the force does not produce the same effect. This is consistent with the hypotheses.

This interaction is not significant for ΔGF_{mean} , which is also consistent with the hypotheses. However, the set of directions significantly impacts ΔGF_{mean} , indicating that ΔGF_{mean} is significantly different depending on the axis along which the load forces are produced. This is explained later with the anistoropy in the coefficient of friction.

The ANOVA tests comparing the Δ differences between training and reproducing show very little difference between the two states. However, there is a significant interaction effect between body orientation and state (training or reproducing) for ΔLF_{mean} during vertical movements, which shows that the effect of orientation is reinforced without feedback, which was expected.

In the experiment, the subjects were trained every other block, benefiting from auditory feedback. In study [6], subjects were trained only in one condition (in 1g gravity). They were then required to reproduce the forces during parabolic manoeuvres producing distinct G-level phases.

Therefore, it could be hypothesized that to observe the gravitational impact, subjects should be trained only in one condition.

Indeed, studies show that too much training can prevent subjects from "unlearning" or sufficiently forgetting between sessions, which can skew reproduction results. For example, research on Ebbinghaus's forgetting curve has demonstrated that appropriate intervals of rest are essential to observe the true effects of forgetting and relearning.[51] If subjects are trained too frequently, they retain too much information from previous sessions, which can prevent the observation of the true behaviours or changes expected in reproduction experiments.

5.2.2 Detailed observations

A. Seated with upward and downward isometric forces

1. ΔLF_{mean}

The mean of ΔLF_{mean} is positive. Even though ΔLF_{mean} is not significantly different from 0, the same trend as in the study [6] is observed, namely a positive ΔLF_{mean} . It could be hypothesized that some variability in the data causes 0 to be included in the confidence interval.

2. ΔGF_{mean}

The asymmetry (Δ) of GF_{mean} is positive but the safety margin is not significantly different from 0.

An anisotropy at the thumb was shown between the upward and downward μ_{static} . Those in the upward direction are greater than those in the downward direction.

Thus, we can write :

$$\begin{aligned}\mu_{static_{upward}} &> \mu_{static_{downward}} \\ \Rightarrow GF_{upward} &< GF_{downward} \\ \Rightarrow \Delta GF_{mean} &> 0\end{aligned}\tag{5.1}$$

The anisotropy in the friction coefficient therefore explains the non-zero and positive ΔGF_{mean} .

3. $\Delta \frac{GF}{LF}_{mean}$

The ratio $\Delta \frac{GF}{LF}_{mean}$ is not significantly different from 0. Thus, no decoupling between GF and LF is observed. This could suggest that, at the sensory motor level, the system ‘understands’ that the load force is different and therefore applies a different grip force, which is inconsistent with [6].

B. Seated with forward and backward isometric forces

1. ΔLF_{mean}

The mean of ΔLF_{mean} is negative and ΔLF_{mean} is significantly different from 0. This is not consistent with the hypotheses of [6]. Nevertheless, other factors could also come into play.

Stiffness is the resistance of a mechanical system (such as an arm) to deformation when subjected to a force. The study [52] suggested that when an horizontal force is applied in a direction where the arm is stiffer, the human body’s muscular and nervous systems interpret this situation as requiring less force to maintain the position or movement. Consequently, the force is perceived as weaker. Conversely, in a direction of lower stiffness, the system interprets that more effort is needed to produce or resist the force, making the force feel greater. Therefore, the perception of force varies depending on the direction of

stiffness, with higher stiffness making the force feel weaker and lower stiffness making it feel greater. The stiffness of a limb decreases the effort required to move or resist a force in the direction of that stiffness.

When a force is applied in a direction of high stiffness, such as extension (forward), extensor muscles like the triceps brachii are more engaged and resist the movement more. This increased resistance provides greater stability, leading the body's muscular and nervous systems to perceive the force as less intense because less effort is needed to maintain the position or counteract the force. In flexion (backward), where stiffness is lower, flexor muscles like the biceps brachii are active, but the perceived effort is higher because the system interprets that more force is required to produce or resist the movement, making the force seem greater. [53]

Therefore, we can write:

$$\begin{aligned}
 & \text{stiffness}_{backward} < \text{stiffness}_{forward} \\
 & \Rightarrow \text{effort}_{backward} > \text{effort}_{forward} \\
 & \Rightarrow \text{perceived LF}_{backward} > \text{perceived LF}_{forward} \\
 & \Rightarrow \text{actual LF}_{backward} < \text{actual LF}_{forward} \\
 & \Rightarrow \Delta LF_{mean} < 0
 \end{aligned} \tag{5.2}$$

Under the hypothesis that the sense of effort required to produce horizontal forces is inversely influenced by arm stiffness, and that the arm is stiffer in the forward direction, the observed results where $\Delta LF_{mean} < 0$ are consistent.

2. ΔGF_{mean}

The asymmetry (Δ) of GFmean is negative but the safety margin is not significantly different from 0.

An anisotropy at the thumb was shown between the forward and backward μ_{static} . Those in the backward direction are greater than those in the forward direction.

Thus, we can write :

$$\begin{aligned}
 & \mu_{static_{backward}} > \mu_{static_{forward}} \\
 & \Rightarrow GF_{backward} < GF_{forward} \\
 & \Rightarrow \Delta GF_{mean} < 0
 \end{aligned} \tag{5.3}$$

The anisotropy in the friction coefficient therefore explains a non-zero and negative ΔGF_{mean} .

3. $\Delta \frac{GF}{LF} \text{ mean}$

The $\Delta \frac{GF}{LF}$ mean is significantly different from 0, meaning that there is a decoupling between LF et GF.

The role of the grip force GF is to prevent slippage. The factors influencing the risk

of slippage are the load force LF and the coefficient of friction μ_{static} . Therefore, a properly "controlled" GF will vary according to the LF and the coefficient of friction. If the friction changes (as is the case here between), the GF will also change to maintain a sufficient safety margin.

Consequently, the GF/LF ratio will change, even if the LF is accurately estimated, with the goal of maintaining a constant safety margin. Thus, a non-zero $\Delta GF/LF$ does not necessarily indicate an error in LF estimation.

C. Supine with upward and downward isometric forces

1. ΔLF_{mean}

The mean ΔLF_{mean} is negative and the ΔLF_{mean} is not significantly different from 0. It was expected that ΔLF_{mean} would be equal to 0 and that ΔLF_{mean} would decrease between seated and supine. Even though the mean is negative, the trend observed here is non-significantly different from 0 with a negative slope. This is therefore consistent with article [6].

2. ΔGF_{mean}

The asymmetry (Δ) of GFmean is negative but the safety margin is not significantly different from 0.

As in the condition seated with upward and downward forces, the anisotropy in the friction coefficient explains the non-zero and negative ΔGF_{mean} .

3. $\Delta \frac{GF}{LF}_{mean}$

The $\Delta \frac{GF}{LF}_{mean}$ is significantly different from 0, meaning that there is a decoupling between LF et GF. As previously explained, this does not provide evidence that the LF estimation used to control the GF was incorrect.

D. Supine with forward and backward isometric forces

1. ΔLF_{mean}

The mean ΔLF_{mean} is negative and the ΔLF_{mean} is significantly different from 0. It was expected that ΔLF_{mean} would be equal to 0 and that ΔLF_{mean} would increase between seated and supine. Even though the mean is still negative, the trend observed here is a positive slope, even if the difference between both is not significant.

This could suggest that the sense of effort modulated by arm stiffness (which makes ΔLF_{mean} negative) overrides the sense of effort modulated by gravity (which was expected to make ΔLF_{mean} positive). However, the sense of effort modulated by gravity might still have a small impact compared to the seated with horizontal forces scenario (where the forces are not affected by gravity), resulting in a positive slope between both body orientation.

2. ΔGF_{mean}

The asymmetry (Δ) of GF_{mean} is positive but the safety margin is not significantly different from 0.

As in the condition seated with forward and backward forces, the anisotropy in the friction coefficient explains the non-zero and positive ΔGF_{mean} .

3. $\Delta \frac{GF}{LF}$ mean

Again, the $\Delta \frac{GF}{LF}$ mean is significantly different from 0, meaning that there is a decoupling between LF et GF. Once again, this does not demonstrate a bad estimation of the LF.

5.3 Link with sensorial feedbacks

As discussed in Chapter 2, sensory feedback has a significant impact on force modulation. Indeed, study [15] showed that GF was tuned with the required LF to lift the object, with adjustments based on the object's friction to maintain a safety margin that prevents slippage. The study [19] also highlighted the critical role of cutaneous afferents in object manipulation, showing that cutaneous feedback is crucial for the maintenance of a secure grip and adaptation of the grip force/load force ratio based on friction at initial contact. Our results have shown that the ΔGF was affected by the anisotropy of the friction coefficient. Therefore, in light of this study, it could be suggested that the non-zero $\Delta \frac{GF}{LF}$ indicates that GF is tuned with LF but is indeed adjusted by friction coefficients in order to maintain a safety margin that prevents slippage.

Moreover, the hypothesis that arm stiffness impacts the sense of effort during horizontal forces suggests that proprioception described as the sense of self-movement, force, and body position, and mediated by proprioceptors, mechanosensory receptors located within muscles, tendons, and joints, could also impact the perception of forces.

5.4 Perspectives

To verify the hypothesis that a non-zero $\Delta \frac{GF}{LF}$ reflects an accurate LF estimation and a GF adjusted for differences in friction coefficients, it could be interesting to test the experiment with objects of varying roughness. This variation would affect the coefficient of friction, allowing to observe if the $\Delta \frac{GF}{LF}$ changes accordingly.

Another study could be conducted by training subjects in only one condition. This would help determine if the haptic illusion created by gravity, as observed in study [6], reappears and how it interacts with the arm stiffness hypothesis in a condition where both are present, for example when performing forward and backward forces in the supine position.

Chapter 6

Conclusion

In this thesis, the main objective was to investigate the impact of gravity on haptic illusions. To achieve this, an experimental study was conducted with 15 participants who were required to perform two tasks. The first task involved creating friction on a manipulandum to analyse the coefficient of friction, which was done at the beginning and end of the experiment. The second part consisted of performing isometric forces under four different conditions. These conditions were defined by the combination of body orientation (seated or supine) and the set of directions (V: upward and downward forces, and H: forward and backward forces). These conditions allowed for testing both the impact of body orientation (and thus the relative axis of gravity with respect to the body) and the impact of the variation in force direction on the forces exerted by the participants.

The results obtained did not always align with the hypothesis that the sense of effort, modulated by gravity, influences the perception of forces. The trends in ΔLF_{mean} approached the expected results, particularly in the slopes linking the values observed in the seated and supine positions, but seemed to be impacted by other factors. One suggested factor is that the sense of effort during horizontal forces is inversely proportional to arm stiffness and may potentially override the sense of effort related to gravity.

Furthermore, the fact that participants were trained in each condition repeatedly may have hindered the observation of different results during the reproduction phase. This suggests that the subjects may not have had enough time to "forget" what they had learned, preventing the effects of gravity from becoming apparent.

Further studies could delve deeper into investigating the results while training the participants in only one condition. If confirmed, these findings could be utilized in the development of human-machine interfaces, as mentioned in Chapter 2, in both the aerospace and medical fields.

Chapter 7

Bibliography

1. dict.cc dictionary : : gravitas : : English-Latin translation. (s. d.). <https://browse.dict.cc/latin-english/gravitas.html>
2. Wikipedia contributors. (2024, 14 avril). Gravity. Wikipedia. https://en.wikipedia.org/wiki/Gravity#cite_note-1
3. Reynolds, J. (2023, 23 juin). Loi de la gravitation universelle. Physigeek. <https://physigeek.com/loi-de-la-gravitation-universelle/>
4. Wikipedia contributors. (2024, 9 avril). Earth mass. Wikipedia. https://en.wikipedia.org/wiki/Earth_mass
5. Wikipedia contributors. (2024a, février 29). Mass concentration (astronomy). Wikipedia. [https://en.wikipedia.org/wiki/Mass_concentration_\(astronomy\)](https://en.wikipedia.org/wiki/Mass_concentration_(astronomy))
6. Opsomer, L., Delhay, B. P., Théate, V., Thonnard, J., & Lefèvre, P. (2023). A haptic illusion created by gravity. *iScience*, 26(7), 107246. <https://doi.org/10.1016/j.isci.2023.107246>
7. Lefèvre P., LEPL1506 - Projet 4 en Génie Biomédical, sur moodle.uclouvain.be, page consultée le 25/02/2024, dernière mise à jour s.d., <https://moodle.uclouvain.be/enrol/index.php?id=1824>
8. Kawato, M. (1999). Internal models for motor control and trajectory planning. *Current Opinion In Neurobiology*, 9(6), 718-727. [https://doi.org/10.1016/s0959-4388\(99\)00028-8](https://doi.org/10.1016/s0959-4388(99)00028-8)
9. McNamee, D., & Wolpert, D. M. (2019). Internal Models in Biological Control. *Annual Review Of Control, Robotics, And Autonomous Systems*, 2(1), 339-364. <https://doi.org/10.1146/annurev-control-060117-105206>
10. Todorov, E. (2004). Optimality principles in sensorimotor control. *Nature Neuroscience*, 7(9), 907-915. <https://doi.org/10.1038/nm1309>
11. Vallortigara, G. (2021). The efference copy signal as a key mechanism for consciousness. *Frontiers in Systems Neuroscience*, 15. <https://doi.org/10.3389/fnsys.2021.765646>
12. McCloskey, D., Ebeling, P., & Goodwin, G. (1974). Estimation of weights and tensions and apparent involvement of a “sense of effort.” *Experimental Neurology*, 42(1), 220-232. [https://doi.org/10.1016/0014-4886\(74\)90019-3](https://doi.org/10.1016/0014-4886(74)90019-3)

CHAPTER 7. BIBLIOGRAPHY

13. Gentili, R. J., Cahouët, V., & Papaxanthis, C. (2007). Motor planning of arm movements is direction-dependent in the gravity field. *Neuroscience*, 145(1), 20-32. <https://doi.org/10.1016/j.neuroscience.2006.11.035>
14. Opsomer, L., Théate, V., Lefèvre, P., & Thonnard, J. (2018). Dexterous Manipulation During Rhythmic Arm Movements in Mars, Moon, and Micro-Gravity. *Frontiers In Physiology*, 9. <https://doi.org/10.3389/fphys.2018.00938>
15. Johansson, R. S., & Westling, G. (1984). Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research*, 56(3). <https://doi.org/10.1007/bf00237997>
16. Flanagan, J. R., & Wing, A. M. (1993). Modulation of grip force with load force during point-to-point arm movements. *Experimental Brain Research*, 95(1). <https://doi.org/10.1007/bf00229662>
17. Themes, U. (2016, 4 juillet). The somatosensory system. Basicmedical Key. <https://basicmedicalkey.com/the-somatosensory-system/>
18. Johansson, R. S., & Flanagan, J. R. (2009). Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nature Reviews. Neuroscience*, 10(5), 345-359. <https://doi.org/10.1038/nrn2621>
19. Augurelle, A., Smith, A. M., Lejeune, T., & Thonnard, J. (2003). Importance of cutaneous feedback in maintaining a secure grip during manipulation of Hand-Held objects. *Journal of Neurophysiology*, 89(2), 665-671. <https://doi.org/10.1152/jn.00249.2002>
20. Johansson, R. (2005). Lightning a match under anesthetic, Lab - Department of integrative medical biology, Umea University. YouTube. <https://www.youtube.com/watch?v=HH6QDOMgqDQ>
21. Kim, K. H. (2022b). A review of haptic feedback through peripheral nerve stimulation for upper extremity prosthetics. *Current Opinion In Biomedical Engineering*, 21, 100368. <https://doi.org/10.1016/j.cobme.2022.100368>
22. Wheat, H. E., Salo, L. M., & Goodwin, A. W. (2004). Human Ability to Scale and Discriminate Forces Typical of Those Occurring during Grasp and Manipulation. *The Journal Of Neuroscience*, 24(13), 3394-3401. <https://doi.org/10.1523/jneurosci.4822-03.2004>
23. Cordella, F., Ciancio, A. L., Sacchetti, R., Davalli, A., Cutti, A. G., Guglielmelli, E., & Zollo, L. (2016). Literature Review on Needs of Upper Limb Prosthesis Users. *Frontiers In Neuroscience*, 10. <https://doi.org/10.3389/fnins.2016.00209>
24. Wijk, U., Carlsson, I., Antfolk, C., Björkman, A., & Rösen, B. (2020). Sensory Feedback in Hand Prostheses : A Prospective Study of Everyday Use. *Frontiers In Neuroscience*, 14. <https://doi.org/10.3389/fnins.2020.00663>
25. Sampath, K. K., Arumugam, A., Yaghi, E., Chidambaranathan, K., & Andersen, P. (2022). The role of virtual reality (VR) with haptic feedback in enhancing physical examination skills of health care students – A systematic review protocol. *International Journal Of Osteopathic Medicine*, 46, 51-54. <https://doi.org/10.1016/j.ijosm.2022.10.008>

CHAPTER 7. BIBLIOGRAPHY

26. Gani, A., Pickering, O., Ellis, C., Sabri, O., & Pucher, P. H. (2022). Impact of haptic feedback on surgical training outcomes : A Randomised Controlled Trial of haptic versus non-haptic immersive virtual reality training. *Annals Of Medicine And Surgery*, 83. <https://doi.org/10.1016/j.amsu.2022.104734>
27. Wikipedia contributors. (2024c, avril 10). Inner ear. Wikipedia. https://en.wikipedia.org/wiki/Inner_ear
28. Wikipedia contributors. (2024a, mars 26). Vestibular system. Wikipedia. https://en.wikipedia.org/wiki/Vestibular_system
29. Wikipedia contributors. (2024b, avril 8). Depth perception. Wikipedia. https://en.wikipedia.org/wiki/Depth_perception
30. Meadows, W. J. (2022, 6 mars). Binocular Cues : What They Are and How They Influence Perception ? (Updated : April 2024). OpticZoo - Best Optics Reviews and Buyers Guides. <https://opticzoo.com/binocular-cues/>
31. Westin, J. (2021, 25 octobre). Perceptual Organization - Perception - MCAT content. <https://jackwestin.com/resources/mcat-content/perception/perceptual-organization>
32. 3D display technology - Principles of three-dimensional vision. (s. d.). <http://www-g.eeng.cam.ac.uk/3d-displays/princip.htm>
33. Zrig, K. (s. d.). La stereoscopie : l'art de la vision en relief. Memoire Online. https://www.memoireonline.com/04/08/1033/m_stereoscopie-art-de-la-vision-en-relief3.html
34. Karanjeet, B. (2022, 28 octobre). HUMAN : SENSE ORGAN, EYE. Help For Entrance. <https://www.helpforentrance.com/2022/02/human-physiology-sense-organs-eye-complete-note.html#gsc.tab=0>
35. Wikipedia contributors. (2024a, mars 15). Proprioception. Wikipedia. <https://en.wikipedia.org/wiki/Proprioception>
36. Proske, U., & Gandevia, S. C. (2012). The Proprioceptive Senses : Their Roles in Signaling Body Shape, Body Position and Movement, and Muscle Force. *Physiological Reviews*, 92(4), 1651-1697. <https://doi.org/10.1152/physrev.00048.2011>
37. Kheradmand, A., & Winnick, A. (2017). Perception of Upright : Multisensory Convergence and the Role of Temporo-Parietal Cortex. *Frontiers In Neurology*, 8. <https://doi.org/10.3389/fneur.2017.00552>
38. Barra, J., Marquer, A., Joassin, R., Reymond, C., Metge, L., Chauvineau, V., & Pérennou, D. (2010). Humans use internal models to construct and update a sense of verticality. *Brain*, 133(12), 3552-3563. <https://doi.org/10.1093/brain/awq311>
39. Bruce, L. L. (2003). Adaptations of the vestibular system to short and long-term exposures to altered gravity. *Advances In Space Research*, 32(8), 1533-1539. [https://doi.org/10.1016/s0273-1177\(03\)90392-9](https://doi.org/10.1016/s0273-1177(03)90392-9)
40. Ward, B. K., Bockisch, C. J., Caramia, N., Bertolini, G., & Tarnutzer, A. A. (2017). Gravity dependence of the effect of optokinetic stimulation on the subjective visual vertical. *Journal Of Neurophysiology*, 117(5), 1948-1958. <https://doi.org/10.1152/jn.00303.2016>

CHAPTER 7. BIBLIOGRAPHY

41. Parabolic flight - NASA. (s. d.). NASA. <https://www.nasa.gov/mission/parabolic-flight/>
42. Krüger, J., Richter, P., Stoltze, J., Strauch, S. M., Krüger, M., Daiker, V., Prasad, B., Sonnewald, S., Reid, S., & Lebert, M. (2019). Changes of Gene Expression in *Euglena gracilis* Obtained During the 29th DLR Parabolic Flight Campaign. *Scientific Reports*, 9(1). <https://doi.org/10.1038/s41598-019-50611-4>
43. Crevecoeur, F., Thonnard, J., & Lefèvre, P. (2009). Forward models of inertial loads in weightlessness. *Neuroscience*, 161(2), 589-598. <https://doi.org/10.1016/j.neuroscience.2009.03.025>
44. White, O., Thonnard, J., Lefèvre, P., & Hermsdörfer, J. (2018). Grip Force Adjustments Reflect Prediction of Dynamic Consequences in Varying Gravitoinertial Fields. *Frontiers In Physiology*, 9. <https://doi.org/10.3389/fphys.2018.00131>
45. Gaveau, J., Berret, B., Angelaki, D. E., & Papaxanthis, C. (2016). Direction-dependent arm kinematics reveal optimal integration of gravity cues. *eLife*, 5. <https://doi.org/10.7554/elife.16394>
46. Crevecoeur, F., Thonnard, J., & Lefèvre, P. (2009b). Optimal Integration of Gravity in Trajectory Planning of Vertical Pointing Movements. *Journal Of Neurophysiology*, 102(2), 786-796. <https://doi.org/10.1152/jn.00113.2009>
47. Types of contractions. (s. d.). Ms. Gallagher's Classroom. <http://msgallagherlhs.weebly.com/types-of-contractions.html>
48. Weber, B., & Stelzer, M. (2022). Sensorimotor impairments during spaceflight : Trigger mechanisms and haptic assistance. *Frontiers In Neuroergonomics*, 3. <https://doi.org/10.3389/fnrgo.2022.959894>
49. Lee, R., Klatzky, R. L., & Stetten, G. (2017). In-Situ Force Augmentation Improves Surface Contact and Force Control. *IEEE Transactions On Haptics (Print)*, 10(4), 545-554. <https://doi.org/10.1109/toh.2017.2696949>
50. Barrea, A., Bulens, D. C., Lefevre, P., & Thonnard, J. (2016). Simple and reliable method to estimate the fingertip static coefficient of friction in precision grip. *IEEE Transactions on Haptics*, 9(4), 492-498. <https://doi.org/10.1109/toh.2016.2609921>
51. Murre, J. M. J., & Dros, J. (2015). Replication and analysis of Ebbinghaus' forgetting curve. *PloS One*, 10(7), e0120644. <https://doi.org/10.1371/journal.pone.0120644>
52. Van Beek, F. E., Tiest, W. M. B., & Kappers, A. M. (2013). Anisotropy in the haptic perception of force direction and magnitude. *IEEE Transactions on Haptics*, 6(4), 399-407. <https://doi.org/10.1109/toh.2013.37>
53. Islam, S. U., Glover, A., MacFarlane, R. J., Mehta, N., & Waseem, M. (2020). The anatomy and biomechanics of the elbow. *Open Orthopaedics Journal*, 14(1), 95-99. <https://doi.org/10.2174/1874325002014010095>
54. Use of OpenAI. (2024). ChatGPTPlus [Large language model]. OpenAI. for correction and revision of text.

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