

Grip force adaptation to static and dynamic torques during object manipulation

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Chapter 1

Introduction and Background

The human hand is an amazing tool. It is one of the most important interface between us and the world by allowing us to touch and manipulate it. Its complexity is certainly similar to its usefulness. To control the manipulatory and the exploratory functions of the hand, the brain needs to collect, to store, and to process adequately a considerable quantity of data about the objects and the environment. In precision grip¹ manipulation (see Fig. 1.1A), all this information is used to control the kinematics and the dynamics of the movement. The latter comprises the tangential forces, regrouped and labeled as *Load force* on Fig. 1.1A, the normal forces to the grasp surface applied by the subject termed as *Grip force*, and potentially load torques if the center of mass is located away from the grip axis.

The models usually used to represent the neural processes controlling the kinematics and the dynamics of the movement are described in the first section of this chapter. The three main sources of sensory information helping for object manipulation are the tactile, the proprioceptive, and the visual feedbacks. They are described in the second section of this chapter. In the third section, microgravity is introduced as a powerful tool to focus on the inertial component of forces and to assess the influence of gravity on the grip force control. The fourth section of this

¹Grip with the index finger and the thumb only.

chapter focuses on the influence of the load torques on the sensorimotor system and specifically on the grip force control. In the last two sections, the thesis content is presented and the scientific communications are listed.

1.1 Motor Control Theories

In this section, one particular theory about the motor control will be described : The internal models. This is not the only theory about motor control but the discussion of the other chapters of this thesis are based on it. An example of another motor control theory is the muscular synergies. It consists of patterns of co-activation of muscles recruited by a single neural command signal. It is a neural strategy of simplifying the control of multiple degrees of freedom (**D’Avella et al.**, 2003; **Latash et al.**, 2007). This way, the motor command is much simpler than if all the muscles had to be controlled individually during the task execution. The basic synergies are responsible for combining the different muscles activation. The motor synergies combine these basic synergies to create more complex movements. Finally, the functional synergies execute movement categories as the prehension. Another theory, states that kinematic and electromyographic patterns are not programmed, but emerge from the dynamic interaction among the system components, including external forces within the designated frame of reference (**Feldman and Levin**, 1995).

1.1.1 Internal Models

Internal models are one way to represent neural processes used to prepare the motor commands and estimate their consequences. The continuous interactions between the limbs and the internal models control the motor system. The inverse model transforms the desired position and the actual position into an appropriate motor command. On the other hand, the forward model processes motor commands to predict future state of the body. In the particular field of object manipulation, the motor commands sent to the muscles of the arm, the hand, and the

fingers to perform the desired movement are the output of an inverse model (see Fig. 1.1c). In contrast, the grip force is controlled in a predictive way thanks to a forward model (**Flanagan and Wing, 1993; Flanagan et al., 1993; Flanagan and Wing, 1997b; Kawato, 1999; Miall and Wolpert, 1996; Wolpert and Flanagan, 2001**).

Grip force regulation is necessary for avoiding any slippage and accidental loss of the object. The grip force must also stay low enough for saving muscular energy and preserving the integrity of the object. According to the second Newton's law, $\vec{F} = m\vec{a}$, the acceleration induces forces, which are tangential to the grip surface for vertical movements. In this chapter, the resultant of the tangential forces present at the finger/surface interface is termed load force (see Fig. 1.1A). As illustrated on Fig. 1.1B, the grip force is modulated synchronously with the load force variation. It is a strong evidence of the presence of a predictive component in the grip force control. Indeed, if the control was only based on the feedback, there would not be synchronized because of the physiological delays. The forward model predicts the movement of the arm and the induced load force depending on the descending motor commands. This prediction makes possible the perfect timing of the grip force modulation with the load force fluctuations.

1.2 Sensory Information Sources for Dextrous Manipulation

The information provided by the somatosensory² and visual systems are determining for an efficient grasp during dextrous manipulation. Thanks to this feedback, the brain can create an internal representation of the object and the environment and maintain this representation up-to-date. The following section describes the tactile, the proprioceptive and the visual feedbacks and their importance for grip force control. Note that even if these three types of feedback are the most important, other feedbacks can provide information to help object manipulation, the auditory system and the vestibular system are two examples.

²The somatosensory system is large, widely spread into the body and comprises number of sensory receptors (e.g. mechanoreceptors, see Section 1.2.1)

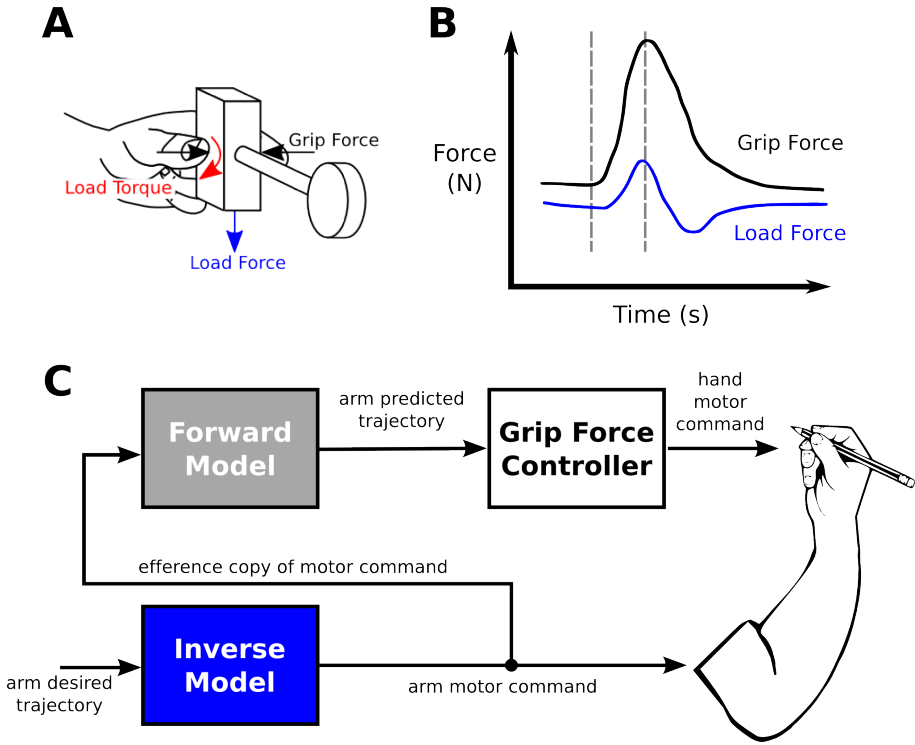


Figure 1.1: A: Schematic representation of the hand holding an object with precision grip. The resultant of the tangential forces are termed load force and represented with the blue arrow. The forces applied by the fingers on the grasp surfaces are termed grip force and represented with the black arrows. The load torque induced by the off-centered mass is represented with the red curved arrow (discussed in Section 1.5). B: Temporal evolution of the grip force in blue and the load force in black showing the anticipative adaptation of the grip force with the load force variation. C: The grip force control depending on the arm movement is generally represented by a combination of an inverse model (in blue) and a forward model (in gray). The inverse model takes the desired trajectory of the arm and computes the motor command to be sent to the muscles. An efference copy of the motor command is sent to the forward model in order to predict the arm trajectory. This arm trajectory prediction is finally used by the grip force controller to program the grip force necessary to avoid object slipping during the arm movement. Adapted from **Kawato** (1999).

1.2.1 Tactile Feedback

The tactile sensors are stimulated when the fingers touch an object. They signal the transformation of the soft tissue to the central nervous system and thus provide information about physical properties of the object. This section begins with a description of the cutaneous mechanoreceptors present on the finger tip. After that, a non-exhaustive list of examples of tactile afferents roles is made to highlight the importance of this sensory modality on the grip force control.

Tactile Mechanoreceptors

The mechanoreceptors are sensory receptors that respond to non-noxious³ mechanical stimuli. These tactile afferent neurons have a large myelinated axon characterized by high conduction velocities ranging from about 20 to 80m/s (**Johansson and Vallbo**, 1983; **Mackel**, 1988). They are classified in four main categories: the slow adapting type I (SA-I) and type II (SA-II), and the fast adapting type I (FA-I) and type II (FA-II). The slow adapting types produce sustained responses to static and low frequency stimulations. In contrast, the fast adapting types only respond to transient events, typically, the onset and the offset of the stimulation. The type I afferents have a small and well defined receptive fields while the type II have wider receptive fields with obscure borders (see Fig. 1.2). There are about 17000 mechanoreceptors innervating the human hand. The most present type is the FA-I type (43%), then the SA-I (25%), the SA-II (19%) and finally the FA-II (13%) types (**Johansson and Vallbo**, 1979).

Digital Afferent Impairment

A efficient way to prove the essential need of a particular source of information is to remove it and observe the consequences. The tactile feedback can be temporarily removed with digital anesthesia. The main impact of such finger impairment is a substantial increase of grip force which induces an elevated ratio between grip force and load force

³A non-noxious stimulus is a stimulus that does not damage tissue and thus causes no pain.

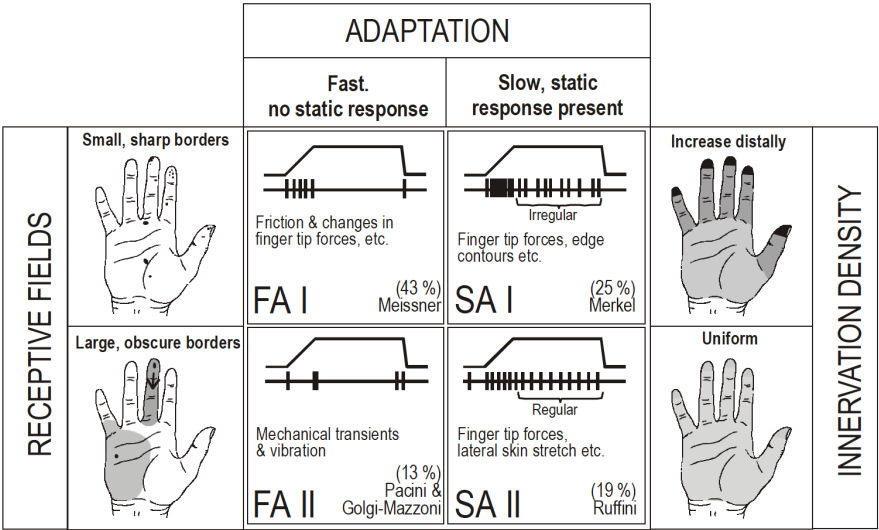


Figure 1.2: The four types of mechanoreceptors are represented with their respective receptive fields on the left, a schematic representation of their impulse discharge in the middle, and their innervation density on the right. The receptive fields of the type I are small and their edges are sharp while the receptive fields of the type II are wider and their edges are fuzzier. On the middle panel (adaptation), the stimulation is represented by the top line of each box. The vertical lines crossing the horizontal axis under the stimulation represent the mechanoreceptors discharges. The fast type responds only during the transient phase of the stimulation. In contrast, the slow type exhibits a static response during the whole stimulation. The innervation density of the type I increases gradually when getting closer to the finger tip, while the type II are distributed uniformly on the hand. From **Johansson and Westling** (1990).

(**Nowak et al.**, 2001). However, the grip force amplitude and timing still anticipate the load force variation during vertical arm movement with a grasped object (**Johansson and Westling**, 1984) using the proprioceptive and visual feedbacks (see Section 1.2.2 and 1.2.3). As illustrated on Fig. 1.3, the digital anesthesia also impedes the conservation of the background level of grip force during repetitive movements (**Augurelle et al.**, 2003b). Another consequence is a disturbed finger placement and control of pinch forces direction (**Monzée et al.**, 2003). When tactile afferents are impaired, significant additional linear and torsional forces appeared. In contrast, without anesthesia, only the grasping and lifting forces are present and the forces in other directions and the torques are negligible.

To sum up, the tactile afferents are necessary for economic scaling of grip force, for sustaining the background level of grip force and for guiding the direction of pinch forces. However, it only has a subordinate role on the precise anticipatory temporal coupling of grip force and load force.

Slip Detection

The tactile afferents detect and signal incipient slips to the central nervous system (**Witney et al.**, 2004). This information allows us to react, increase our grip force (**Johansson and Westling**, 1984) and reduce the acceleration of the hand (**Saels et al.**, 1999). The latency between the onset of a slip and the force adjustment is ranged between 0.06 and 0.08s, which suggests that the underlying neural mechanisms operate highly automatically without being processed by the brain. A slip occurrence is well illustrated on Fig. 1.3. During this experiment, **Augurelle et al.**, subjects with digital anesthesia dropped the object ended by dropping the object in 70% of slip occurrences. It suggests, that tactile afferents are strongly involved in slip detection.

The slips are rapidly signaled to the central nervous system via the tactile afferents in order to adjust the grasping force and the kinematics of the upper limb.

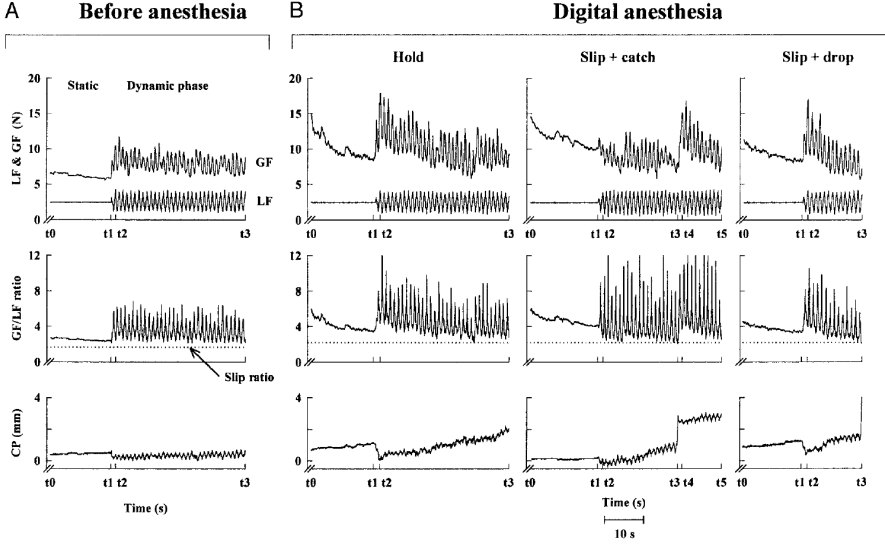


Figure 1.3: Effect of digital anesthesia of grip force during vertical oscillatory movements. Temporal evolution of the grip force, the load force, the ratio GF/LF and the center of pressure during an vertical oscillatory movements are shown in four different situations (one situation by column). The first column is the control situation of a manipulation without anesthesia. The slip ratio is represented by the dotted line. The second to the fourth columns show the traces of a trial under digital anesthesia. During this trial, no slip occurred. On the third column, a slip occurred at t_3 but the subject achieved to recover a stable grasp. On the last column, an irrecoverable slip occurred and the subject dropped the object. From **Augurelle et al. (2003b)**.

Surface Geometry

Important information about the geometry of the contact surface of the manipulated object are provided by the digital feedback. The structural properties of the contact surface have a major impact on the friction between the object and the fingers. For instance, the rotational friction depends directly on the surface curvature, which influences the grip force (**Goodwin et al.**, 1998). It has been shown that the geometry information provided by the cutaneous afferents are quite precise. Humans are able to discriminate small difference of position stimuli ($0.55mm$ for a $5.80mm$ radius sphere, **Wheat et al.** (1995)) and small change of orientation (5.4° for a $1.92mm$ radius cylinder, **Dodson et al.** (1998)). Of course, the visual feedback can also provide complementary information about the surface geometry. But the grip force is adjusted to different object shapes even in absence of visual information. Note that, the inverse has also been demonstrated (**Jenmalm and Johansson**, 1997; **Jenmalm et al.**, 2000). It means that the tactile feedback plays an important role on this grip force adaptation to object shape in conjunction with visual feedback.

Forces Direction

The digital feedback helps to control the forces direction depending on the goal of our actions. For instance, to lift up an object, we first need to apply a force normally to the object surface then a vertical force for the lifting phase. The direction of the forces present at the interface between the finger and the target object influences the firing pattern of the digital afferents (**Birznieks et al.**, 2001; **Macefield et al.**, 1996). These firing patterns provide the CNS with a feedback triggering muscle activation specifically tuned for the direction of the load (**Häger-Ross et al.**, 1996).

1.2.2 Proprioceptive Feedback

The proprioception provides information on the mechanical forces produced by the body itself and more specifically in the musculoskeletal system (**Purves and Coquery**, 2005). In contrast to the cutaneous

receptors which respond to external stimulations, the proprioceptors are literally the receptors "sensitive to themselves". Their main function is to inform continuously and precisely about the state of the limbs and the body. Three types of proprioceptors exist. The muscle spindles are present in the belly of the muscle and detect length changes. The Golgi organs sense changes in muscle tension and are spread among the skeletal muscle. Finally, the joint receptors are fast adapting mechanoreceptors placed within or around the joints.

Contribution to the Grip Force control

The proprioceptive feedback plays an important role in the grip force modulation with the load force fluctuations. As described above, the digital anesthesia does not impede the grip force profile to be timed with load variations (**Augurelle et al.**, 2003b; **Monzée et al.**, 2003). It suggests that this grip force modulation is partially possible thanks to the proprioceptive information. Indeed, it has been shown that patients with polysensory neuropathy⁴ are not able to make the grip force profile matching the load variation during a movement (**Nowak et al.**, 2004; **Monzée et al.**, 2003). This incapacity to modulate the grip force effectively is illustrated on Fig. 1.4 where the grip force of the patient (GL) is not synchronized with the acceleration and the load force. It confirms that even if the grip force modulation is preprogrammed depending on the descending motor commands, the proprioceptive feedback is necessary to signal its effectiveness and update the internal models.

1.2.3 Visual Feedback

The visual system provides the CNS with a huge quantity of valuable information about our surroundings. A quick look is sufficient to know about the position, the color, the size, the shape and the texture of an object and even its direction and velocity if it is moving.

⁴Complete loss of the senses of touch, vibration and pressure, and kinaesthesia in the neck trunk, and upper and lower limbs.

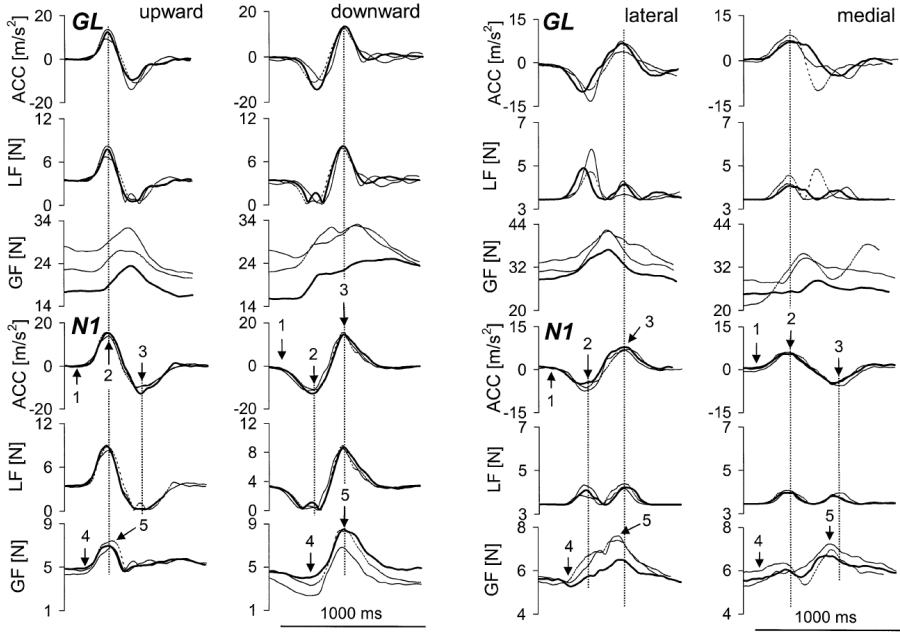


Figure 1.4: Temporal traces of the acceleration, the grip force and the load force for four types of movement and for two subjects : a deafferented (*GL*) and a healthy (*N1*) subject. The vertical dotted lines signal the accelerations peaks. The grip force modulation is timed with the load force fluctuations for *N1* and much less synchronized for *GL*. From Nowak et al. (2004).

Contribution to the Grip Force Control

The grip force necessary for manipulating an object can be estimated only by looking at the object. It is even possible to rapidly update the internal object weight representation and adapt the lifting forces by observing at someone else lifting the object (**Reichelt et al.**, 2013). The shape, the texture and the size of the object directly influence the friction and the forces needed to manipulate it. The visual feedback provides the CNS with information about the structural properties of the object and the CNS adapts the forces adequately (**Jenmalm and Johansson**, 1997). This a priori information can sometimes be misleading and can influence the tactile and proprioceptive perception erroneously. A well known example is the size-weight illusion (**Clément**, 2014; **Davis and Roberts**, 1976; **Jones**, 1986; **Murray et al.**, 1999; **Pierce et al.**, 1970). When two objects with the same mass but different volumes are lifted, the smallest is always reported as being the heaviest. This effect is present even if no haptics cues are given to the subject meaning that the visual information itself can produce the illusion. However, after several trials of this particular situation the sensorimotor system adapts adequately the grip force to the real mass while the perceptual illusion stays persistent (**Flanagan and Beltzner**, 2000). The visual feedback is then an important source of information to preprogram and to correct the forces applied on the object and its potential unreliability can be compensated by the other feedbacks.

1.2.4 Multisensory Integration

All the sensory sources discussed above can be used simultaneously to provide a more precise feedback. This is called multisensory or multimodal integration. The latter is a wide research field that describes how the different sensory feedbacks are combined and integrated by the nervous system (**Angelaki et al.**, 2009; **Ernst and Banks**, 2002; **van Beers et al.**, 1999; **Stein et al.**, 2009). The modalities combination enables us to have a more precise representation of objects and to be more efficient manipulating them.

1.3 Motor Learning and Adaptation

Motor learning is a combination of motor and cognitive processes related to practice and experience that lead to almost permanent changes in motor performances. The movements tend to become smoother and more accurate which is necessary for complicated tasks as writing and playing base-ball but also really important for calibrating simple movements like reflexes. Sensitivity of error-detection and strength of movement schema are variables that reinforce motor program formation (**Adams**, 1971; **Izawa and Shadmehr**, 2011). A difference can be made between the learning which can be defined as acquiring the ability to perform appropriately an action which can be considered as permanent and the temporary processes that affect motor behavior during practice that can be called "motor adaptation" (**Shadmehr et al.**, 2010). The latter can be considered as component of the general concept of motor learning. In the next chapters, we discuss grip force adaptation during repetitive tasks rather than motor learning in general.

1.4 Microgravity

Since we are born, we are used to manipulate object in presence of a constant level of gravity. The gravity level has a strong influence on the dynamics and the kinematics of our movements and it must be taken into account even unconsciously to manipulate objects effectively. The influence of the gravity can be observed by altering it or even producing microgravity. In object manipulation, this particular condition is very useful to focus on the inertial components of forces and torques. Indeed, the weight of an object is negligible when the gravity level is close to zero. This means that when an object is hold without moving, the tangential forces at the finger/surface interface are absent.

Parabolic flight is a way to conduct research under reduced gravity condition. The experimental material and the experimenters are placed on board of an aircraft. This aircraft produces the weightlessness sensation by following an elliptic trajectory relative to the center of the Earth (see Fig. 1.5). During 20 seconds, the aircraft and its payload are

in free fall. Thus, the aircraft does not exert any ground reaction force on the material and the experimenters, which produces the sensation of weightlessness.

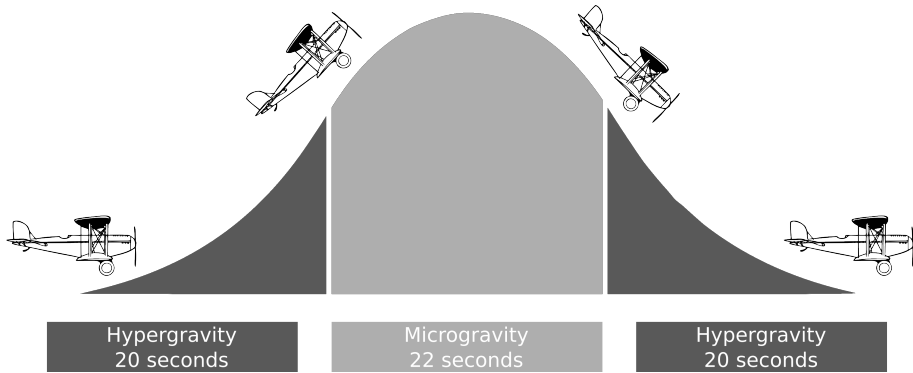


Figure 1.5: Schematic representation of a parabola performed by the aircraft during a parabolic flight. The microgravity phase (light gray) happens at the top of the parabola and lasts about 22 seconds. A phase of hypergravity (dark gray) precedes and follows the microgravity phase.

Microgravity does not deeply modify the strategies of grip force control. Indeed, it has been demonstrated that the gravity is centrally represented and used for arm movement planning (**Papaxanthis et al.**, 1998) and that the grip force modulation with load force is still present under novel load conditions as microgravity (**Hermsdörfer et al.**, 1999, 2000). A new level of gravity is rapidly learned and the grip force is adapted according to this new condition (**Augurelle et al.**, 2003a). Interestingly, the ratio between the grip force and the load force is impacted by the gravity level. A repetitive task in microgravity condition also revealed a difference in time scales of static and dynamic components of grip force (**Crevecoeur et al.**, 2009). This suggests that the grip force controller processes both components independently. Weightlessness condition may sometimes have strong impacts on the results obtained during experiments, for instance, on mass estimation and discrimination (**Ross and Reschke**, 1982). Nevertheless, in object manipulation, the gravity level seems to be taken into account by the CNS.

1.5 Load Torque

The load torques induced by holding an unbalanced object (see Fig. 1.1A) are deeply involved in the sensorimotor processes controlling the grip force. So far, we have described the influence of the load force variations and other parameters such as the gravity on the grip force control. However, load torques are frequently present when manipulating objects and must be taken into account to adjust the grip force depending on the desired action. We can either exploit those torques to change the position of the grasped object or, on the contrary, try to limit the rotations. In both cases, grip force is constrained to be modulated with the load torque fluctuations as it has to be modulated with the load force. It is true for predictable (**Goodwin et al.**, 1998; **Jenmalm et al.**, 2000; **Kinoshita et al.**, 1997; **Wing and Lederman**, 1998) and unpredictable (**De Gregorio and Santos**, 2013) load torque variations. This grip force fine tuning is possible thanks to the encoding of the load forces and load torques by the sensory afferents (**Birznieks et al.**, 2010a; **Khamis et al.**, 2015; **Redmond et al.**, 2010). The first part of this section describes the influence of the load torque on the grip force (based on **Kinoshita et al.** (1997)) and the second one gives more details about the anticipative grip force adjustment to load torque variations (**Goodwin et al.**, 1998; **Wing and Lederman**, 1998).

1.5.1 Influence on the Grip Force

The minimum required grip force necessary to avoid rotational slips when holding an unbalanced object is directly proportional to the magnitude of the load torque⁵ (**Kinoshita et al.**, 1997). To demonstrate this, it has been asked to subjects to hold an object in presence of an off-centered mass (see Fig. 1.1A) and to let it rotates discontinuously. Between each rotational slips, the subjects had to maintain the object in a constant position (see Fig. 1.6A). The rotational slips made by the subjects gradually reduced the load torque by steps close to $5mNm$ (millinewton meter) until the object no longer rotated. The level of grip force at the very beginning of each slip step (vertical dashed lines on

⁵The entire section (1.5.1) is based on **Kinoshita et al.** (1997).

Fig. 1.6A) represented exactly the minimum grip force required to avoid rotational slip at this level of load torque. This particular level of grip force is termed slip force (in red on Fig. 1.6A). It can be observed that the slip force decreased with the load torque. This linear correlation (see Fig. 1.6B) has been confirmed by **Wing and Lederman** (1998).

The linear correlation between the slip force and the load torque is influenced by the level of load force (see Fig. 1.6C). Indeed, a higher load force tends to shift the line up and to reduce its slope. This relationship between the slip force, the load torque and the load force is not purely additive. The slip force is influenced by an the interaction between load torque and the load force which can be modeled as follows :

$$F_{slip} = aLF + b|LT| + cLF|LT| \quad (1.1)$$

where, F_{slip} is the slip force, LF is the load force, LT is the load torque and a , b and c are coefficients reflecting the friction properties. Using a curve fitting method, this model was determined to be the best one beside two others models proposed in the study.

Similarly to the slip force, the grip force used to hold an unbalanced object also depends on the load torque. According to the results of another experiment (**Wing and Lederman**, 1998), in which the object was released between each load torque level, we are able to maintain an adequate level of grip force to keep the object orientation and avoid rotational slips.

1.5.2 Predictive Control

Load torques are anticipated by the grip force controller and combined with the load forces prediction to produce an adequate grip force. When an unbalanced object as shown in Fig. 1.1 and Fig. 1.7A is tilted, the instantaneous grip force is coordinated with the instantaneous load torque throughout the tilting movement (**Goodwin et al.**, 1998). In this experiment, Goodwin et al., asked the subjects to lift up the object represented on Fig. 1.7A aligning the rod vertically and pointing the exchangeable mass downward (see *Lift and hold* phase on the Fig. 1.7B). After that, they had to tilt the object up producing a load torque in-

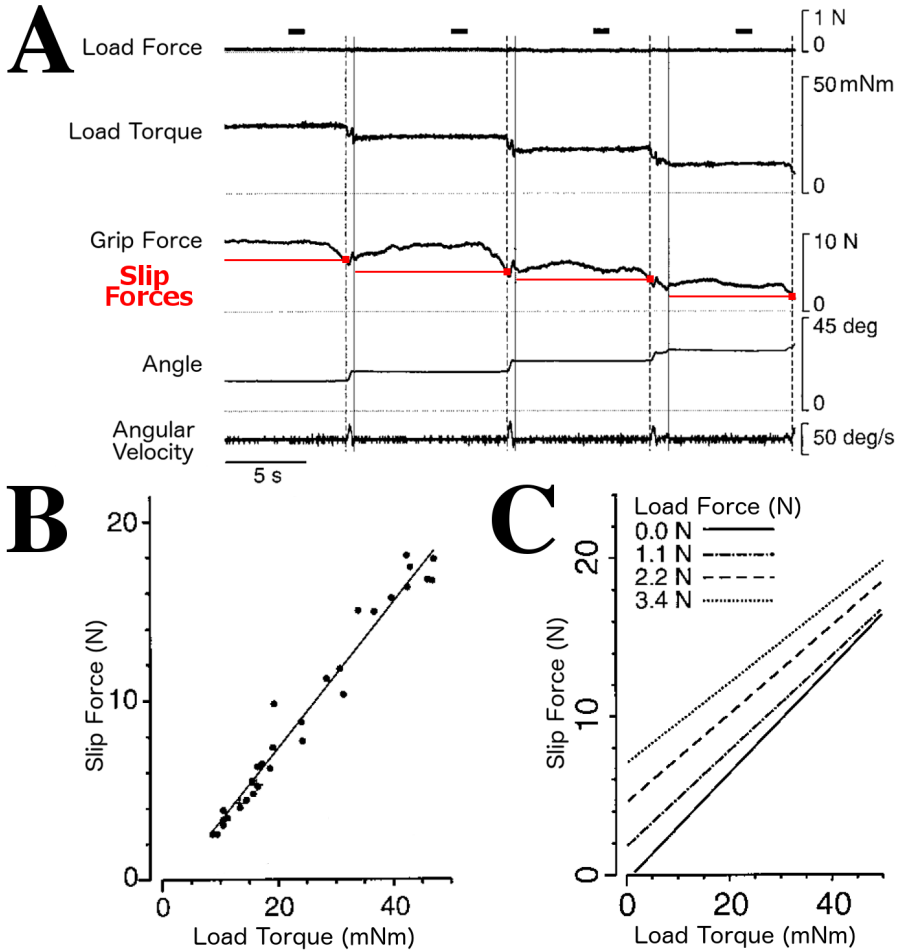


Figure 1.6: A: Temporal traces of load force, load torque, grip force, angle and angular velocity. Load force stayed null during all this particular trial as the weight of the object was counter-balanced with another weight through a pulley. Load torque, grip force and angle evolved gradually according to the experiment design (more details in the text). Slip forces are represented in red. A peak of angular velocity occurred at each load torque step as the subject let the object rotating by decreasing his/her grip force. B: Slip forces as a function of load torques. C: Linear correlations between slip force and load torque for different load force levels. Adapted from **Kinoshita et al.** (1997).

crease (see *Tilt* phase Fig. 1.7B). During the *tilt* phase, the grip force was increased synchronously with the load torque. No change in load force occurred and then the load force could not be the reason of the grip force regulation. It confirms that the sensorimotor system adjusts effectively the grip force to the torsional load variation. The results of Goodwin et al. also suggests that the sensorimotor system anticipates the load torque evolution. Indeed, the tilting time to get to the target angle was not influenced by the different exchangeable masses tested. It means that the motor commands sent to the muscle took into account the load torque and were programmed to produce similar kinematics profiles.

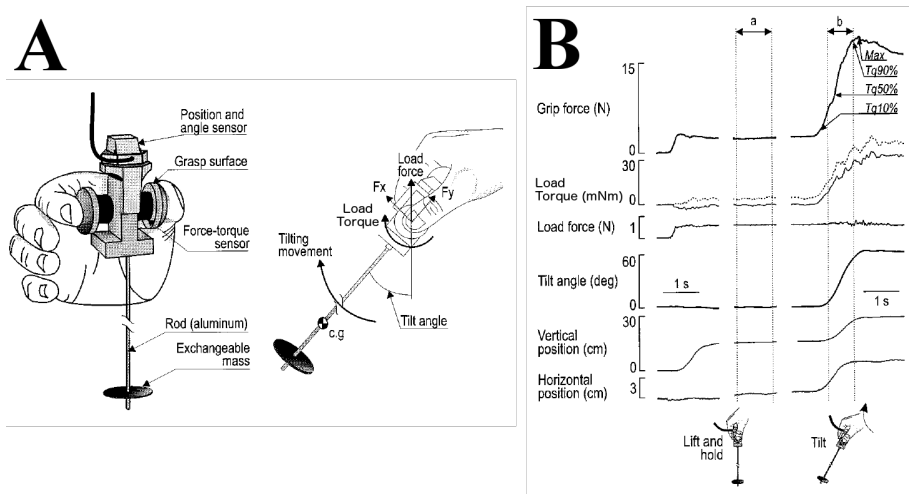


Figure 1.7: A: Representation of the object manipulated by the subject on the left and of the tilting movement, forces, and torques on the right. B: Temporal traces of the forces and the kinematics signals. After the lift, the load force stayed constant at a level equivalent to the weight of the object. During the *tilt* phase, the grip force increased synchronously with the load torque. Adapted from **Goodwin et al.** (1998).

This load torque prediction is also used to adapt anticipatively the grip force (**Wing and Lederman, 1998**). It has been demonstrated by asking subjects to perform horizontal movements with an object similar to the one presented on Fig.1.7A. The horizontal acceleration induced a load torque variation. The level of load torque produced by the

movement depends directly on the distance between the fingers and the center of mass (moment arm). According to the results described above (**Goodwin et al.**, 1998; **Kinoshita et al.**, 1997), the peak of grip force and its rate were correlated with the moment arm. Moreover, the peak of grip force rate always occurred too early after the movement onset to be the result of a feedback process. It confirms that, the grip force adjustments compensate in a anticipative fashion for the load torques that tended to destabilize an unbalanced object.

This correlation between the peak of grip force rate and the moment arm and the correlation between the grip force and load torque are based on general rules present in the sensorimotor system. Indeed, this relationship between grip force and load torque is present from the first manipulation of an unbalanced object (**Wing and Lederman**, 1998). Moreover, these rules are updated with repetitions, which is highlighted by an increase of peak of grip force rate across the trials. The hypothesis of general rules is reinforced by the ability to interpolate an appropriate level of grip force when manipulating at a novel level of load torque.

1.6 Thesis Content

The objective of the present work was to further investigate the control strategies during object manipulation in presence of load torques. The studies described in the next chapters are based on the background presented in this introduction and especially in the previous section (1.5). This thesis is organized into five sections.

The introduction provided an overview of different concepts involved in object manipulation and grip force control.

Chapter 2 addresses the influence of static and dynamic torques on the adaptation of grip force control. It has been shown that the grip force is modulated in a similar way with the load torque as with the load force (see Section 1.5). However, little is know about the adaptation of the grip force across repetitive task in presence of a load torque. To investigate whether the load torque influences this adaptation, we assessed the grip force evolution across repetitive vertical grip-lift. This evolution was compared with two similar manipulations, one in absence of load

torque and the other one after previous adaptation to the presence of a torque. The results show that the grip force adaptation is slowed down when a load torque is present.

Chapter 3 follows the results of the previous study by addressing the role played by the inertial component on the slow grip force adaptation. Even if the effect of the load torque on the grip force adaptation rate is demonstrated, its origin remains unclear. It could be induced by a poor ability to extract information about tangential constraints during the stationary hold in presence of a load torque. Alternatively, inertial torque experienced during movement may also potentially disrupt the grip force adjustment. A vertical point-to-point task was performed in microgravity with and without off-centered mass to compare the grip force adaptation rate when only inertial torque was present. The reproduction of a slower adaptation when manipulating torques suggests that the presence of load torques experienced during movement may alter our internal estimates of required grip force.

Chapter 4 states the hypothesis that the difference in control strategies when a load torque is present comes from a poor ability to discriminate load torques. An uncertain discrimination could induce a more cautious decrease of grip force across repetitive movements. The hypothesis has been tested in the context of a grip-lift task similar to the one of Chapter 2 and in the context of a passive stimulation. Indeed, a poor ability to discriminate load torque was found during the active task. However, this bad discrimination was not due to an incapacity of the sensory system as the discrimination during the passive stimulation was much better.

Finally, a summary of the main findings and a general discussion are provided in Chapter 5. Open questions and insights about related future work is proposed to conclude the present thesis.

1.7 Publications and Communications

1.7.1 Published

- Crevecoeur, F., Giard, T., Thonnard, J.-L., and Lefèvre, P. (2011),

Adaptive control of grip force to compensate for static and dynamic torques during object manipulation., *Journal of neurophysiology*, 106, 6, 2973–81

- Giard, T., Crevecoeur, F., McIntyre, J., Thonnard, J.-L., and Lefèvre, P. (2015), Inertial torque during reaching directly impacts grip-force adaptation to weightless objects, *Experimental Brain Research*

1.7.2 In preparation

- Giard, T., Crevecoeur, F., Thonnard, J.-L., Lefèvre, P. (2015), Load torque discrimination is better during passive stimulation than active grip-lift.

1.7.3 Proceedings

- Giard, T., Thonnard, J.-L., Lefèvre, P. (2012), Grip force control strategies during slow load variations in presence of a tangential torque. *Annual meeting of the Society for Neural Control of Movement*, Venice, Italy
- Giard, T., Thonnard, J.-L., Lefèvre, P. (2012), Grip force control strategies during slow load variations. *Annual meeting of the Society for Neuroscience*, Genval, Belgium
- Giard, T., Thonnard, J.-L., Lefèvre, P. (2012), Object manipulation : Collisions in presence of a tangential torque as part of the "Enhanced Virtual Reality Stimulator Workshop". Brussels, Belgium
- Giard, T., Crevecoeur, F., McIntyre, J., Thonnard, J.-L., Lefèvre, P. (2012), Grip force adaptation to dynamic torques during object manipulation in weightlessness. *Annual meeting of the Society for Neuroscience*, New-Orleans, USA
- Giard, T., Crevecoeur, F., McIntyre, J., Thonnard, J.-L., Lefèvre, P. (2013), Grip force adaptation to dynamic torques during object

manipulation in weightlessness. *32nd Benelux Meeting on Systems and Control*, Houffalize, Belgium

- Giard, T., Crevecoeur, F., McIntyre, J., Thonnard, J.-L., Lefèvre, P. (2013), The kind of mechanical loads during pointing directly impacts grip force adaptation in weightlessness. *PAI/VII/19 DYSCO Study Day*, Mons, Belgium

Chapter 2

Adaptive control of grip force to compensate for static and dynamic torques during object manipulation¹

Abstract

Manipulating a cup by the handle requires compensating for the torque induced by the moment of the mass of the cup relative to the location of the handle. In the present study, we investigated the control strategy of subjects asked to perform grip-lift movements with an object with centre of mass located away from the grip axis. Participants were asked to lift the manipulandum with a two-fingers precision grip and stabilize it in front of a visual target. Subjects showed a gradual and slow adaptation of the grip force scaling across trials: the grip force tended to decrease slowly and the temporal coordination between grip force and load torque rates displayed gradually better-coordinated patterns. Importantly, this

¹Crevecoeur, F., Giard, T., Thonnard, J.-L., and Lefèvre, P. (2011), Adaptive control of grip force to compensate for static and dynamic torques during object manipulation., *Journal of neurophysiology*, 106, 6, 2973–81

adaptation was much slower than the stabilization of the same parameters measured either when no torque came into play or after previous adaptation to the presence of a torque. In contrast, the maximum rotation induced by the torque was efficiently controlled after only few trials, and an unexpected decrease in the tangential torque produced significant overcompensation. An unexpected increase in torque produced a consistent opposite effect. This shows that the compensation for the dynamic torque was based on an anticipatory dynamic counter-torque produced by the arm and wrist motor commands. The comparatively slow stabilization of grip force control suggests a specific adaptation process engaged by the presence of the torque. This paradigm including tangential torques clearly constitutes a powerful tool to extract the adaptive component of grip control during object manipulation.

2.1 Introduction

With the thumb opposing the index, humans have the ability to grasp and manipulate objects. More specifically, this grip permits to modulate the force developed to hold objects stable in our hands. Indeed, the force required to hold an object depends on many factors, including the object weight, the mechanical and frictional properties of the skin/object interface and the inertial constraints induced when the object is accelerated. Several studies have characterized the sensorimotor control of precision grip and shown that in general, the grip force exhibits a predictive compensation for the load constraints induced by the interaction with the object. Such anticipatory scaling is known to be based on internal models, prior knowledge of the object properties and cutaneous feedback of the mechanical properties of the fingertip/object interface (**André et al.**, 2010; **Augurelle et al.**, 2003b; **Crevecoeur et al.**, 2010b; **Danion and Sarlegna**, 2007; **Flanagan and Wing**, 1993, 1995, 1997b; **Johansson and Westling**, 1984; **Westling and Johansson**, 1984; **Witney et al.**, 2004).

Many studies have focused on the tight coupling between the grip force and the load force when the latter is the only constraint that comes into play. But in most situations encountered on daily bases, ma-

nipulating an object also implies the anticipation of static and inertial torques. A typical example is when we grasp a cup by the handle, a clear objective is to minimize the swinging of the cup in order to avoid spilling the content. In such situation, the torque induced by the moment of the object centre of mass relative to the grip axis must be taken into account in order to maintain a stable grip. Several strategies have been reported in studies examining multi-digit grasp configurations. In general, the Central Nervous System is capable to coordinate the force distribution under the fingers and control the moment arm induced by the spatial distribution of fingers location in order to compensate for external torques (**Lukos et al.**, 2007; **Santello and Soechting**, 2000; **Shim et al.**, 2006; **Zatsiorsky et al.**, 2002). In the context of bi-digital precision grip with the thumb and index finger, previous results showed that the grip force modulation also compensates for tangential torques, and scales as a function of torque variations (**Goodwin et al.**, 1998; **Kinoshita et al.**, 1997; **Wing and Lederman**, 1998). In particular, although categorical changes in movement and grip force parameters following practice have been reported earlier (**Wing and Lederman**, 1998), there has been to date no investigation of the trial-by-trial adaptation of grip force and movement control in the presence of constraints that tend to rotate the object.

To investigate this issue, the present paper addresses the control of grip-lift movements of an object producing tangential torques at the finger/object interface. Our results enhance that the anticipation of inertial torques is based on a dynamic counter torque applied by the arm and wrist motor commands. In addition, our results also unravel an adaptive control of grip force that is directly attributable to the presence of a torque, suggesting a particular role of sensory feedback of torque constraints for the central control of grip force.

2.2 Methods

2.2.1 Subjects

Twenty-nine healthy human subjects between 23 and 46 yrs participated in this study after giving written informed consent. The experimental protocol was approved by the ethics committee of the Université catholique de Louvain (Belgium). The subjects were separated in four groups corresponding to the four following experiments. The first two experiments involved the manipulation of an object with center of mass away from the grip axis, inducing torques at the finger/object interface (Experiments 1 and 2). The third experiment sought to dissociate the effect of the torque from the effect of the high level of grip force developed by the subjects tested during the first experiment. More details about this control experiment are given hereafter (Experiment 3). In all experiments, subjects were instructed to use a two-fingers grasp. The grip aperture was 4.5cm and the force sensors were covered by brass. Each experiment consisted of series of grip-lift movement with comfortable inter-trial duration (10sec to 1min). Subjects were encouraged to take breaks as often as needed in order to avoid fatigue. A fourth experiment was conducted to estimate the minimum grip force required to avoid slippage in each experimental condition.

Experiment 1

Subjects ($n = 8$) were required to perform grip-lift movements with the right hand by using precision grip. The start of each trial was cued by a visual target placed 20cm above the starting position. The geometry of the manipulandum was not symmetrical and subjects could clearly see the off-centered mass prior to the experimental run. The off-centered mass was a cylinder of 100g placed 10cm away from the grip (Fig. 2.1) and the total mass of the manipulandum, including the 100g cylinder, was 430g . Subjects were asked to perform a series of 60 grip-lift movements towards the aforementioned visual target. After the 60th trial, the subjects were blindfolded and the experimenter replaced the off-centered mass by a cylinder with identical shape but reduced mass

(40g). This procedure was intended to produce an unexpected change in static and inertial torques. Then, visual feedback was recovered and the subjects performed another series of 60 grip-lift trials with the 40g off-centered mass.

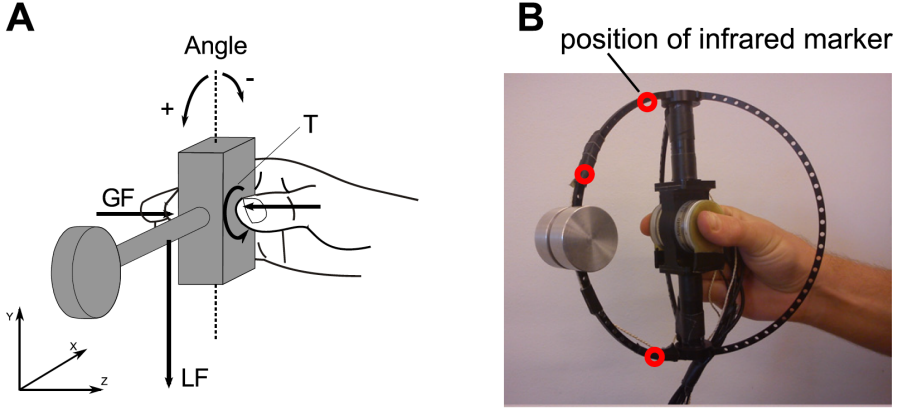


Figure 2.1: (A) Schematic representation of the instrumented object equipped with an off-centered mass that moved the center of mass away from the grip axis. The study focuses on the grip force (GF), the load force (LF), the tangential torque measured along the grip axis (T) and the angle induced by the static and dynamic torques. (B) Picture of the manipulandum with schematic representation of the position of the infrared markers used for motion tracking.

Experiment 2

This experiment addressed the interaction between the absolute torque level and the previous exposure to the presence of a torque in the adaptation of grip force parameters. Subjects ($n = 8$) performed the same task as did the subjects involved in the first experiment, except that they started to manipulate the manipulandum equipped with the 40g off-centered mass. After the 60th trial, the 40g cylinder was replaced by the 100g cylinder following identical procedures as in the first experiment. Reversing the order allowed us to compare the adaptation to the control of static and dynamic torques with and without previous exposure to another torque level. In Experiments 1 and 2, only the off-centered mass was changed, inducing a change in torque but also a

small change in net mass (14%). This design was retained in order to preserve overall shape of the manipulandum.

Experiment 3

The grip forces that subjects initially developed to hold the manipulandum with the 100g off-centered mass were substantially higher than the range commonly reported when studying the grip-load force coupling. It was thus necessary to compare the effect observed in the presence of a torque with subjects' behavior without torque, but with similar force recruitment. To do so, we defined an equivalent mass: a mass for which subjects would produce similar levels of grip force, but without torque. We followed a theoretical approach based on the computation of the tensor of tangential constraints at the finger-object interface. We computed the force density on the contact surface with and without off-centered mass. By using a classical argument of linear addition, the force density tensors corresponding to a centered mass only, or a torque only, were summed in order to estimate the overall force density tensor. Then, we defined the equivalent mass as a centered mass that would produce identical integrated square norm of forces density as the one computed in the presence of a torque. We approximated the finger-object contact surface as a disc of radius 9.3mm, compatible with experimental observations (Andre et al., 2011). Knowing that the total mass of the manipulandum (including the off-centered mass) was 430g, we estimated that the equivalent mass was about 1.6kg. The details of the computation are provided in Appendix B. The subjects involved in this control experiment ($n = 6$) were asked to perform a series of 60 grip-lift movements with the equivalent mass.

Experiment 4

This experiment was designed to examine the minimum grip force required in each configuration of the manipulandum tested in Experiments 1 to 3 (100g off-centered, 40g off-centered, and with the equivalent mass). Participants ($n = 7$, different from other experiments) were asked to hold the manipulandum stationary in precision grip for more than 5s

and then release the grip gradually until slipping occurred, either in rotation when an off-centered mass was present, or in translation with the equivalent mass. Each subject performed 10 grip-release trials with each configuration (30 in total).

2.2.2 Data Collection and Analysis

The custom manipulandum (ESAGLM, Arsalis, Louvain-la-Neuve, Belgium) was equipped with two 3-dimensional force and torque sensors (mini 40 F/T transducers, ATI, Industrial Automation, NC, USA). We collected the tangential and normal forces at the interface between the fingers and the manipulandum, as well as the tangential torques generated by the off-centered mass along the grip axis (T in Fig. 2.1). The grip force was defined as the mean of the normal components measured by each sensor. The load force was the sum of the tangential constraints measured on each sensor. The analyses reported hereafter focus on the vertical component of the load force. The load torque was also defined as the sum of the tangential torques relative to the grip axis on the right and left sensors. Each signal was collected at 800Hz and digitally low-pass filtered with zero-lag 4th order Butterworth filter with cut-off frequency set to 20Hz .

The position of the manipulandum was measured with a motion-tracking device (Codamotion, Charnwoods Dynamics, Leicestershire, UK) collecting the position of infrared markers placed on the manipulandum as illustrated in Fig. 2.1. From the position of the three markers, we computed the location of the centre of the spherical structure, corresponding to the centre of the grip axis. The vertical coordinate and velocity of this point are considered hereafter. Regarding the angle induced by the torque, the movements were projected into the vertical plane orthogonal to the grip axis (the plane containing X and Y axes in Fig. 2.1) and the angle was computed from the change in orientation of the vector joining the grip axis to the off-centered mass. The position of the markers was sampled at 200Hz and digitally low pass filtered with 4th order zero-lag Butterworth filter with 20Hz cut-off frequency.

The movement onset (t_0) and end (t_f) were determined when the

vertical velocity exceeded or dropped below 1% of its peak value computed on each individual trial. The tangential torque recorded from the sensors was corrected in order to take into account the actual torque relative to the fingertips centre of pressure according to procedures described in other studies (**André et al.**, 2010; **Kinoshita et al.**, 1997). The centre of pressure was also utilized to address possible compensation for the external torque by adjusting the finger configuration within the allowed grip surface. Indeed, the 40mm diameter of forces sensors leaves some room for adjustments of finger location. The time derivatives of force and torque signals were also extracted from numerical differentiation. The static grip force was the average grip force in a time window from $t_f + 1s$ to $t_f + 2s$. The presence of an effect across the trials was addressed by means of classical one-way ANOVA. The characterization of learning curves for the grip force (GF) was based on exponential fits computed on pooled subjects' data versus the trial number (n) as follows:

$$GF(n) = a_0 + a_1 e^{a_2 n} \quad (2.1)$$

This equation was fitted to the maximum and static values of the grip force across each individual trial. The significance of the exponential fit was based on whether or not the estimated 95% confidence interval of a_2 included 0. The data and fits presented below show the maximum and static values of grip force normalized for each subject to their individual means across the last 10 trials performed with the 100g off-centered mass for Experiments 1 and 2, and to the last 10 trials for Experiment 3. This normalization procedure was used for illustration purpose as it partially reduces the inter-subjects variability. However, the estimates of adaptation rates were identical when the fits were computed on raw grip force parameters. The comparison of two populations was based on non-parametric Wilcoxon ranksum test. The coordination of forces and torques was based on cross-correlation of the derivative of force and torque signals.

The minimum grip force necessary to hold the manipulandum stationary was estimated as follows (Experiment 4). When an off-centered mass was present, the mean and standard deviation of the tangential

torque was computed in a 1s time window preceding the initiation of grip force release. Then, we determined the time when the load torque dropped below the mean minus 2 standard deviations for at least 200ms. The grip force at the beginning of this 200ms time window was averaged across the 10 repeats to estimate the grip force at slipping. The procedure used to determine the minimum grip force with the equivalent mass was identical, except that the mean and standard deviation of the load force were considered instead of the tangential torque.

2.3 Results

Experiment 1

A typical example is illustrated in Fig. 2.2. The movement exhibited standard kinematics with single peak, bell-shaped velocity profiles (Fig. 2.2, position and velocity). Some subjects (3/8) presented significant decrease in peak velocity across the first 60 trials based on linear regressions but there was no consistent tendency across subjects. Three individual subjects showed significant increase in peak velocity across the second series (trials 61 to 120). However, pooled subjects' data revealed no significant variation of the velocity peak neither within each series of 60 trials with the two different off-centered masses, nor across the 120 consecutive trials (ANOVA, $F < 0.85$, $P > 0.87$). The peak inertial external torque presented no significant tendency across trials within each series of lifting movements (ANOVA, $F < 0.45$, $P > 0.5$). There was no migration of the centre of pressure across trials within each series of lifting movements (ANOVA, $F < 0.6$, $P > 0.5$). Across all subjects, the average location of centre of pressure was within a radius of 7.5 mm relative to the centre of the force sensors. Thus, movement kinematics, grip configuration and tangential torque tended to be stable across trials, which is critical to interpret changes in grip force production as gradual adaptation to the tangential torque.

Most subjects reported that it was quite hard to hold the object with the 100g off-centered mass. Indeed, they developed very high levels of grip force ranging from 42N to 58N across the subjects (average across

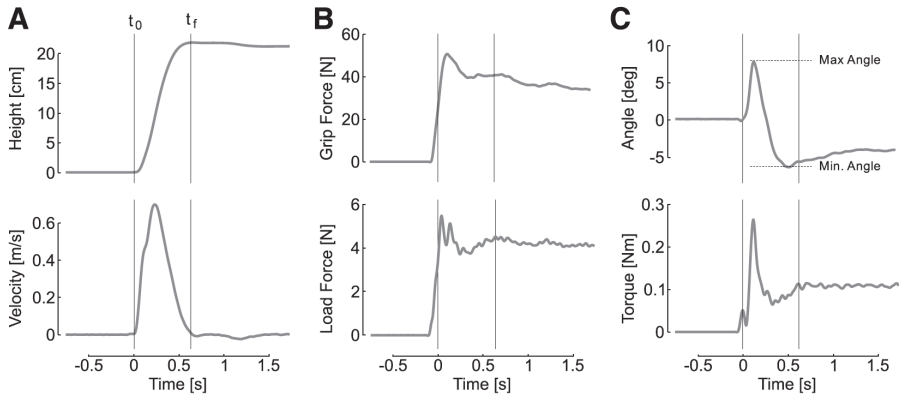


Figure 2.2: Representative traces of one grip-lift trial. (A) Position and velocity profiles as a function of time. (B) Grip force and load force traces. (C) Change in angle and tangential torque during the lifting movement. The vertical lines illustrate the estimated movement onset and end. The maximum and minimum angles are illustrated.

the trials 2 to 5). These values are presented in Fig. 2.3A along with the values measured at the end of the first series (average across the trials 57 to 60), and the last 4 trials with the 40g off-centered mass (average across trials 117 to 120). The maximum grip force presented highly significant decrease across the two series of trials, from trial 1 to 60 with the 100g off-centered mass, and from trial 61 to 120 with the 40g off-centered mass (ANOVA, $F > 3.36$, $P \ll 0.001$). The static grip force presented highly significant decrease during the first series of 60 trials (ANOVA, $F = 6.07$, $P \ll 0.001$), and did not show significant evolution across the second series (ANOVA, $F = 1.19$, $P = 0.17$). Besides the results of the ANOVA analyses, all exponential fits computed on the grip force parameters were significant (maximum and static grip force, during the first and second series). These fits are plotted in Fig. 2.3B and 3C for data normalized for each individual subject to their maximum and static values averaged across the trials 51 to 60. Interestingly, the time constants ($|1/a_2|$, see Eqn. 2.1) were higher in the first series than in the second series: the estimated time constant for the maximum and static grip force during the first series were 42 and 39 trials respectively (trials 1 to 60, 100g off-centered mass), and 5 and 8 trials during the

second series for the maximum and static grip force values, respectively (trials 61 to 120, 40g off-centered mass).

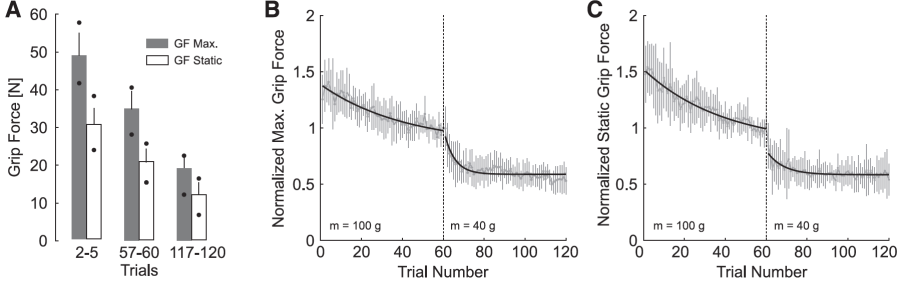


Figure 2.3: (A) Raw values of maximum and static grip force, at the beginning of the experiment, at the end of the first series of 60 trials, and at the end of the second series. The bars indicate one SD and the dots are the minimum and maximum values across subjects. (B) Time course of the maximum grip force across trials (mean $\pm$ SD across the 8 subjects). (C) Time course of the static grip force across trials (mean $\pm$ SD). For each individual subject, the values were normalized to the last 10 trials of the series with 100g off-centered mass (see Methods). In panels B and C, the black lines represent the first order exponential fits.

As another evidence for a gradual, rather slow adjustment of grip force, we computed the cross correlation between the grip force rate, load force rate and load torque rate during the first grip-lift series (trials 1 to 60 with the 100g off-centered mass). Fig. 2.4A shows grip force, load force and load torque profiles normalized to their peak values for the first (top) and last (bottom) trials executed by one representative subject in this series. Fig. 2.4B shows the derivative of the signals plotted in Fig. 2.4A. Time zero corresponds to the estimated movement onset. These plots clearly show a better-coordinated pattern at the end of the first series, which we quantified by looking at the peak cross-correlation between the derivatives of the grip force, load force and load torque profiles. The peak correlation between the grip force rate and the load torque rate presented significant variation (ANOVA, $F = 1.85$, $P < 0.001$), and significantly increased across trials (linear regression, $P < 0.001$, Fig. 2.4C). There was no significant effect of the trial number on the peak correlation neither between the grip force and load force rates, nor between the load force and load torque rates (ANOVA, $F < 1.19$,

$P > 0.1$). The grip force rate lagged the load force rate by $26 \pm 23ms$ and led the load torque rate by $51 \pm 42ms$ (mean $\pm$ SD across subjects). Time lags did not show significant variation across trials (ANOVA, $F > 0.9$, $P > 0.6$).

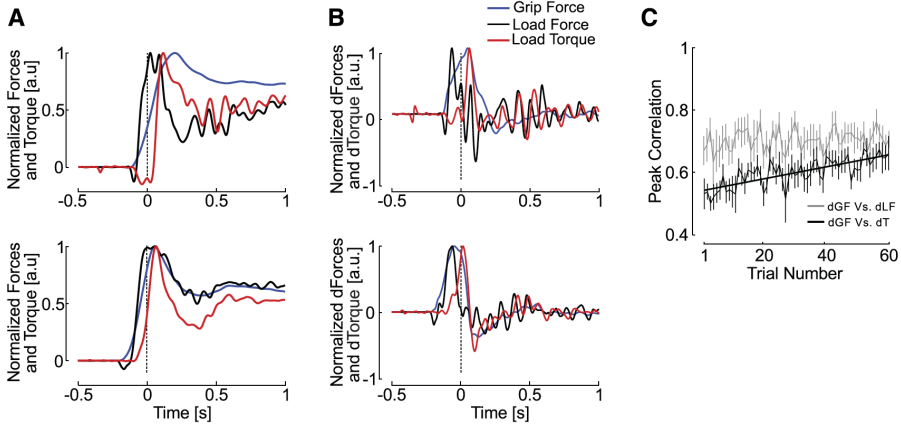


Figure 2.4: (A) Grip force, load force and load torque normalized to their maximum values for the first (top) and last (bottom) trial of one representative subject with the 100g off-centered mass. (B) Time derivatives of the signals plotted in panel A normalized to their peak values. (C) Peak cross-correlation between the grip force rate and the load force rate (grey) and between the grip force rate and the load torque rate in black. The mean $\pm$ SEM across the 8 subjects is represented for clarity.

Importantly, while grip force was gradually (and relatively slowly) adjusted to the tangential torque in both dynamic and static phases, the tilt of the manipulandum was successfully controlled by subjects from the first trials. There was no significant evolution of the maximum angle of the manipulandum within each series of grip-lift trials with the two different off-centered masses (Fig. 2.5A). There was a significant variation of the maximum angle between the first and second series that can be directly attributed to the change in off-centered mass. However, the minimum swing angle also varied significantly between the end of the first series and the beginning of the second series (Wilkoxon ranksum test, $P < 0.01$, Fig. 2.5B, inset shows the means $\pm$ SD across subjects of the 10 last and first trials of each series, respectively). The examination of the peak acceleration and velocity before the end of the first series

(10 last trials with 100g off-centered mass) and the beginning of the second series (10 first trials with 40g off-centered mass) revealed no significant changes in peak acceleration and peak velocity, suggesting a limited impact of the change in net mass in the kinematics of the lifting movement (Wilcoxon rank sum test, $P > 0.13$). Thus the change in angle provides evidence that subjects dynamically varied the torque applied on the object in order to counter the inertial torque induced by the acceleration of the off-centered mass. The change in minimum angle at the beginning of the second series reveals that the counter torque was applied in anticipation of the inertial torque.

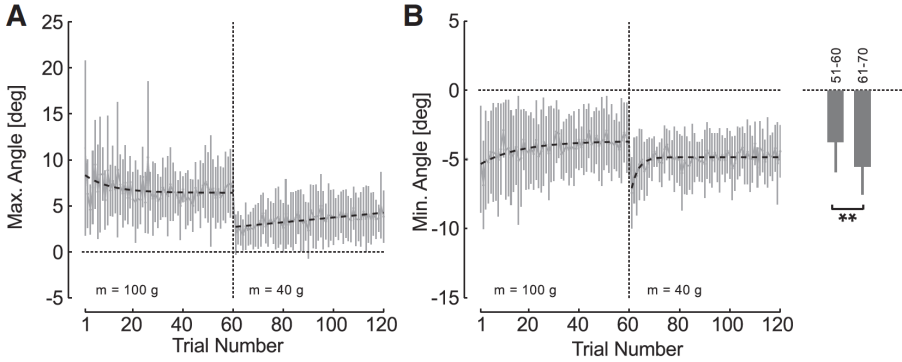


Figure 2.5: (A) Maximum swing angle across trials. (B) Minimum swing angle (means $\pm$ SD). The dashed traces correspond to the first order exponential fits that were not significant, but give the general tendency. The inset of panel B represents the comparison between the last 10 trials of the first series and the first 10 trials of the second series.

Experiment 2

Overall, the results of this experiment were qualitatively similar to those of Experiment 1. The rotation of the manipulandum was well controlled whereas grip force adjustments exhibited adaptation across trials. The absolute grip force values tended to be smaller at the beginning of each series than in Experiment 1, but gradually decreased towards values comparable to the ones observed in Experiment 1 after adaptation (compare Fig. 2.3A with Fig. 2.6A). The maximum grip force presented significant effect across trials in the first series (ANOVA, $F = 2.85$,

$P < 0.001$). The analysis of variance failed to reveal significant variation of maximum grip force for the second series (100g off-centered mass). The static values of grip force presented significant evolution across trials in the first and second series ($F > 1.75$, $P < 0.005$). Besides ANOVAs, the exponential fits computed on normalized pooled subjects' data were significant in the four series ($P < 0.05$). The estimated time constants in the first series were 13 and 10 trials for the maximum and static values, respectively (40g), and 11 and 9 trials for maximum and static values in the second series. In comparison with experiment 1, adaptation in the second series in both cases is clearly facilitated by the prior manipulation performed in the first series.

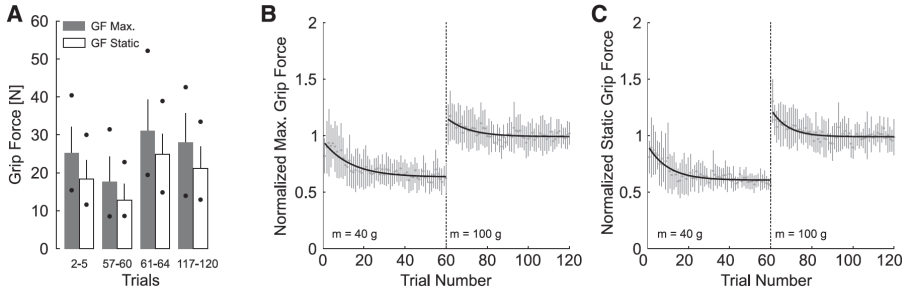


Figure 2.6: Same plots as Fig. 2.3 for the second experiment. (A) Raw values of grip force, the bar indicates one SD and the dots are the minimum and maximum values across subjects. (B) Normalized maximum grip forces as a function of the trial number (mean $\pm$ SD across subjects). We used the same normalization procedure consisting in normalizing relative to the last 10 trials of the series performed with the 100g off-centered mass. (C) Same as B with the static grip force.

As shows Fig. 2.7, the maximum and minimum angle displayed little to no variation across trials in each series (one way ANOVA, $F < 1.2$, $P > 0.13$). The change in angle at the transition was compatible with our hypothesis that participants dynamically anticipated the inertial torque: the maximum angle (Fig. 2.7A) in the first trial of the second series (100g after 40g) exhibited a dramatic increase due to the unexpected change in off-centered mass (Wilcoxon Ranksum test, comparison between trials number 60 and 61, $P < 0.01$). The minimum angle (Fig. 2.7B) also increased suggesting that the anticipative counter

torque could not compensate for the unexpected higher torque (inset of Fig. 2.7B, $P < 0.05$).

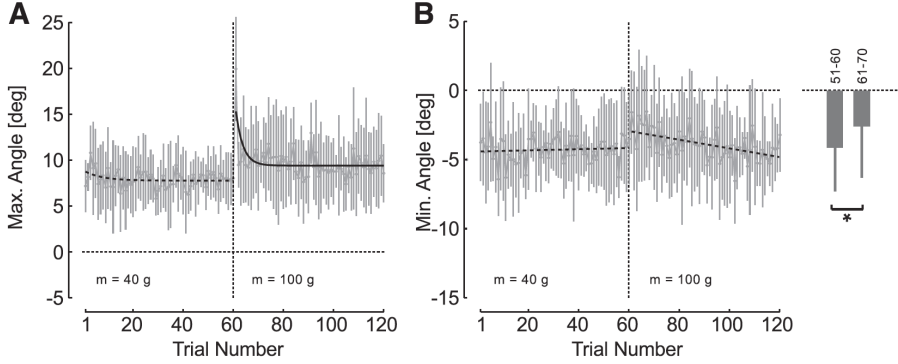


Figure 2.7: Same as Fig. 2.5 for the second experiment with 40g off-centered mass manipulated in the first series, followed by the 100g off-centered mass. (A) Maximum angle across trials (mean $\pm$ SD across subjects). Dashed trace indicate non-significant tendency from the exponential fit. The solid trace indicates that the increase induced by the unexpected change in mass enforced significant exponential trend. (B) Minimum angle across trials. The inset illustrates the comparison between the last 10 trials of the first series and the first 10 trials of the second series.

Experiment 3

This control experiment investigates grip force adaptation when no torque comes into play, but with a mass intended to produce high levels of grip force. Fig. 2.8A shows that the subjects developed peak and static grip force that were comparable to the level measured during the first experiment: subjects' average maximum grip force across the trials 2 to 5 ranged between 30N and 51N. This control experiment critically emphasizes that peak and static values of the grip force also present highly significant decrease when the force recruitment approaches the one observed in Experiment 1, even in the absence of torque (Fig. 2.8B and C, ANOVA, $F > 2.28$, $P < 0.001$). The exponential fits were also significant (normalized data, Fig. 2.8B-C). However, the estimated time constants were substantially shorter in this case: the results were 11

and 9 trials for the peak and static values of the grip force, respectively. This suggests a 4-fold faster adaptation process than when a tangential torque is present despite similar force recruitment at the beginning of the two series. Thus, the decrease in peak and static grip force observed in the presence of the torque in Experiment 1 (first series) is partially due to the high level of grip force required, but the slow decrease rate may be mostly attributed to the presence of the tangential torque (Experiment 1, first series vs. Experiment 3). The tangential torque also clearly influenced the stabilization of the peak grip force level. Indeed Fig. 2.3A and 2.8A show that the maximum grip force stabilized to lower values in Experiment 3 than in Experiment 1.

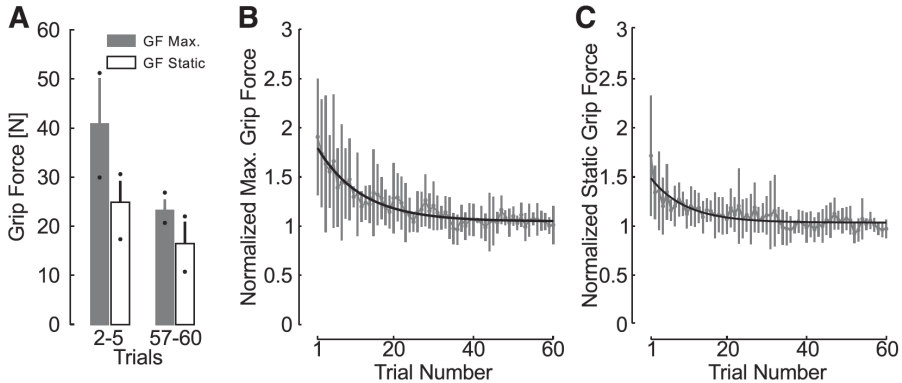


Figure 2.8: Same plot as Fig. 2.3 for the third experiment. (A) Raw values of grip force. (B) Evolution of the maximum grip force across trials normalized to the 10 last trials. (C) Evolution of the static grip force across trials normalized to the 10 last trials. Standard deviations across the subjects are represented.

Experiment 4

The minimum grip force to hold the manipulandum stable before slipping was $16.7 \pm 3N$ with the 100g off-centered mass, $8.5 \pm 2.6N$ with the 40g off-centered mass, and $16.8 \pm 2.8N$ with the equivalent mass (mean $\pm$ SD across subjects). In all, these results enhance the following important points. First the theoretical approach used to estimate the equivalent mass based on an approximation of the local constraints

at the skin-object interface is validated by this experiment as we found strikingly similar mean values of grip force at slipping onset in the two conditions (100g off-centered and equivalent mass). Second, this experiment suggests that subjects used a greater safety margin when tangential torques come into play, as the static grip force in Experiment 1 with 100g off-centered mass stabilized at about 123% of the minimum estimated above (20.5N), and the static grip force in Experiment 2 with the same mass stabilized at the same level (125%, 21N). In contrast, the subjects manipulating the equivalent mass stabilized at 16.9N. This result suggests that the different values for safety margins must be considered with caution. Indeed, the grip force developed by subjects involved in Experiment 3 was about 100% of the measured slip force, which is too close to the minimum grip force required reported above. Such small safety margin is likely due to the fact that different subjects were involved in the different experiments. However, as similar slip forces were found for the 100g off-centered mass and for the equivalent mass, a direct comparison of force levels developed by subjects in each conditions can be done. Such comparison reveal that the grip forces developed with the 100g off-centered mass were significantly greater than those measured with the equivalent mass (one-tail Wilcoxon Rank Sum test, $P < 0.05$). The grip force developed to hold the manipulandum with 40g off-centered mass revealed even higher safety margins with reproducible measurements across Experiments 1 and 2. With this mass, we observed stabilization of the static grip force at 143% of the slip force in Experiment 1 (12.5N) and at 150% (12.8N) in Experiment 2.

2.4 Discussion

The results clearly demonstrate the two following facts. First, the anticipatory compensation for inertial torque involves a dynamic application of a counter-torque by the arm motor commands in addition to the grip force modulation. Second, the grip force adjustment stabilizes slowly, whereas the dynamic swinging of the manipulandum produced by the inertial torque is almost immediately compensated. Notably, we demonstrated that the torque played a critical role in the grip force adaptation

process. Indeed, previous exposure facilitates the adaptation of grip force scaling (Experiment 2, see Section 2.3) and the stabilization observed for similar levels of force, but without any torque, was appreciably faster (Experiment 3, see Section 2.3).

Our results are compatible with previous findings on grip force adjustment to the presence of static or inertial torques (**Goodwin et al.**, 1998; **Kinoshita et al.**, 1997; **Wing and Lederman**, 1998). **Wing and Lederman** (1998) reported changes in some parameters between the first and last movement that consisted in horizontal transport of an object designed to produce inertial torques during the acceleration phase (the center of mass was below the grip axis). The authors reported a decrease in baseline grip force and an increase in grip force rate. However, **Wing and Lederman** did not observe a strong effect on the grip force peak, which could be attributed to the differences in protocol (hold and transport versus grip-lift in the present study). Goodwin and colleagues addressed the grip force modulation in a “grip-tilt” task, isolating the changes in torque in a paradigm equivalent to the grip-lift task when focusing on the grip force modulation with the load force. In general, these previous studies enhanced a tight coupling between the grip force and the load torque. The present study replicates this relationship and, importantly, focuses also on the compensation for inertial torque by looking at the control of the swing of the manipulated object. This original contribution allowed us to enhance the dynamic application of a counter-torque and the comparatively slow decrease of the grip force parameters with a detailed analysis of the effects of torque and force recruitments on adaptation rates.

The variation in minimum angle after changing the off-centered mass clearly provides evidence for an anticipatory application of a counter-torque during the dynamic phase of the lifting movement. Indeed, if that minimum angle corresponded to an over-compensation for the maximum angle based on a feedback control mechanism, we would not observe such sudden change in minimum angle. In Experiment 1 (decrease in external torque, see Section 2.3), the change in minimum angle reflects that the actual torque was smaller than the counter torque applied by the subjects in an anticipative way. Indeed, the first trial with the 40g off-

centered mass should be considered as a catch trial, unraveling the anticipatory application of a dynamic counter torque. The second experiment confirmed this result (increase in external torque): the minimum angle increased after increasing the off-centered mass, showing that the anticipatory compensation for inertial torque was not sufficient to stabilize the manipulandum against the torque induced by the 100g off-centered mass. In particular, this result emphasizes that the compensation for tangential torque was not solely based on the stiffening of the grip.

Another strategy to compensate for the presence of a torque was recently emphasized when the grip configuration is not constrained to a two-finger grasp configuration: a coordinated distribution of forces applied by the fingers when using multi-digit grasp (**Santello and Soechting**, 2000; **Shim et al.**, 2006; **Zatsiorsky et al.**, 2002), and the control of the position of the fingers on the manipulated object (**Fu et al.**, 2010; **Lukos et al.**, 2007, 2008) can induce a moment in the grip that compensates for external torques. This strategy efficiently allowed subjects to minimize the roll angle of the manipulated object without dramatically increasing the grip force as in the present study. Importantly, Lukos and colleagues emphasized that the control of digit placement was an important component of the control of the grasp movement. Here, the object configuration and the constrained position of the fingers on the sensors limited the possibility to vary the moment of the grip from the location of the fingers contact points. Altogether, these and previous findings show that object manipulation relies on strategies including spatial control of digit placements and modulation of arm and wrist motor commands in addition to the grip force modulation.

The present study seems in contradiction with previous results on adaptation rates of grip force and movement control (**Flanagan et al.**, 2003) : grip force modulation rapidly anticipated vertical loads proportional to horizontal velocity (rate < 5 trials), although movement control stabilized much later (rate > 25 trials). In the present experiment, we observed an opposite tendency with fast stable movement control while the peak grip force stabilized more slowly, indicative of the slower adaptation of the predictive component. Although there is no clear theoretical context capable to reconcile the two studies, we

may speculate that the present experiment inverted the complexity of the predictor/controller components: compensating for a torque is a very common situation for arm motor commands (e.g. a cup, a hammer, a racket etc. all produce torques) whereas the use of a two-finger grasp with such tools is highly unusual. In contrast, linear loads used by Flanagan and colleagues are quite usual for precision grip control, while vertical forces proportional to horizontal velocity is a less common situation. However, further investigations are needed to further elucidate whether tangential torques can be at the origin of such differences between the adaptation rates of prediction and control components.

One implication for motor control theory is that the sensorimotor strategies underlying object manipulation could be considered in a more general way. One classical view states that the prediction of inertial constraints output by an internal forward model is processed by a grip controller, which modulates the grip force accordingly (**Kawato**, 1999). When there is no torque, the arm motor commands that move the object and the arm motor commands that contribute to maintaining the grip could hardly be dissociated since both produce forces aligned with the direction of motion. In the present paradigm, the arm motor commands that anticipate the inertial constraints were uncovered by changing the off-centered mass, revealing that, in addition to the grip force modulation, a dynamic counter-torque was applied in order to compensate for the inertial torque. Nonetheless, it is known that the Central Nervous System uses internal models of interaction torques to control multi-joint dynamics in various contexts, including voluntary reaching, rapid motor responses or postural stance (**Gribble and Ostry**, 1999; **Hollerbach and Flash**, 1982; **Hsu et al.**, 2007; **Kurtzer et al.**, 2008). The present study suggests that skillful object manipulation is part of a global control scheme based on internal models of joint interaction dynamics, which extends to the presence of a manipulated object.

A second main implication is that the shape of the torsional constraints at the finger-object interface is taken into account for the grip force adjustment. Indeed, the fingertips are innervated with peripheral encoders of mechanical events (**Birznieks et al.**, 2001; **Johansson and Flanagan**, 2009; **Witney et al.**, 2004), and torques in particular

(**Birznieks et al.**, 2010b), conveying critical cutaneous feedback. Kinoshita and colleagues (**Kinoshita et al.**, 1997) showed that the grip force accounts for the presence of both tangential torque and tangential force. However, the effect of each factor could hardly be dissociated since increasing both tangential torque and force increases the resulting constraints at the finger/object interface. Thus, on the one hand, the peripheral apparatus encoding rotational constraints exists, but little was known as whether this information impacted the central control of grip force as linear loads of similar amplitude. On the other hand, our study provides behavioral evidence for different adaptation rates with or without tangential torque despite similar force recruitment (Experiments 1 and 3), as well as an interaction between the level of the torque and a previous exposure to an off-centered mass in the adaptation process (Experiments 1 and 2). Afferent feedback from fingers and arm muscles may also provide information about the torque. However, we showed by looking at the control of angle that adaptation to kinematics control was fast and could therefore hardly interfere with grip force adjustments. Altogether, this suggests that the specific pattern of local skin deformation, in addition to the intensity of the deformation, is a pivotal component of sensorimotor control of precision grip.

Why this adjustment evolved slowly across trials remains unanswered. Even with 40g manipulated first, a time constant of 13 trials suggests that the steady level is reached after about 40 trials, in agreement with Fig. 2.6. It is however clearly due to the presence of a torque that interacts with the level of force required to hold the object stable, and produced a level of static grip force after adaptation that was quite high relative to the minimum grip force required to hold the manipulandum stationary ($> 120\%$). Several factors can be at the origin of such slow decrease. First, we should acknowledge that the use of a two digits grasp with such levels of force is highly unusual and possibly alters the learning. Another possible origin for such slow decrease is that the norm of local constraints induced by the tangential torque at the finger/object interface increases as a function of the distance to the centre of pressure, whereas the pressure under the fingers decreases as a function of the same distance (**Monzée et al.**, 2003). Thus, close to the boundary

of the contact surface between the fingertips and the object, the fact that lower pressure counteracts higher constraint density could induce more micro-slips, encouraging subjects to maintain an excessive level of grip force and slowing down the learning. Importantly, our results emphasize that the classical grip-lift paradigm extended to the presence of an off-centered mass may provide a powerful mean to address the adaptive sensorimotor control of grip, with obvious applications in clinical, developmental and fundamental studies.

Chapter 3

Inertial torque during reaching directly impacts grip force adaptation to weightless objects¹

Abstract

A hallmark of movement control expressed by healthy humans is the ability to gradually improve motor performance through learning. In the context of object manipulation, previous work has shown that the presence of a torque load has a direct impact on grip force control, characterized by a significantly slower grip force adjustment across lifting movements. The origin of this slower adaptation rate remains unclear. On the one hand, information about tangential constraints during stationary holding may be difficult to extract in the presence of a torque. On the other hand, inertial torque experienced during movement may also potentially disrupt the grip-force adjustments, as the dynamical constraints clearly differ from the situation when no torque load is present. To address the influence of inertial torque loads, we instructed healthy

¹Giard, T., Crevecoeur, F., McIntyre, J., Thonnard, J.-L., and Lefèvre, P. (2015), Inertial torque during reaching directly impacts grip-force adaptation to weightless objects, *Experimental Brain Research*

adults to perform visually guided reaching movements in weightlessness while holding an unbalanced object relative to the grip axis. Weightlessness offered the possibility to remove gravitational constraints and isolate the effect of movement-related feedback on grip force adjustments. grip force adaptation rates were compared with a control group who manipulated a balanced object without any torque load and also in weightlessness. Our results clearly show that grip force adaptation in the presence of a torque load is significantly slower, which suggests that the presence of torque loads experienced during movement may alter our internal estimates of how much force is required to hold an unbalanced object stable. This observation may explain why grasping objects around the expected location of the centre of mass is such an important component of planning and control of manipulation tasks.

3.1 Introduction

With the repetition of a movement, grip force is adapted depending on the specificities of the task (**Flanagan et al.**, 2003; **Nowak et al.**, 2004; **Danion et al.**, 2012). For instance, during a grip-lift task, the finger forces applied on the lifted object during stationary holding decrease with practice. This decrease in grip force typically stabilizes above the minimal force needed to avoid slipping, which reflects a safety margin dependent upon contextual factors and on the mechanical properties at the interface between the skin and the manipulated object (**Johansson and Westling**, 1984; **Westling and Johansson**, 1984). Previous work shows that the presence of a torque load has an important impact on this adaptation rate, which is much slower than in the absence of torque load (see Chapter 2).

Besides the level of grip force used during stationary holding in reaction to the gravitational tangential constraints, the grip force is modulated depending on the additional inertial tangential forces during the movement (**Flanagan and Wing**, 1993, 1997b; **Flanagan et al.**, 1993). In addition to these tangential forces, torque loads are present in many situations and have an impact on the grip force control (**Goodwin et al.**, 1998; **Kutz et al.**, 2009; **De Gregorio and Santos**, 2013).

These tangential forces and torques result from gravitational and inertial components. In addition, it has been shown in earlier studies that grip force is dynamically modulated according to the load-force variation due to object acceleration (**Flanagan and Wing**, 1993, 1997b; **Augurelle et al.**, 2003a; **Crevecoeur et al.**, 2010b; **Danion et al.**, 2013).

Mechanical constraints during object manipulation can be decomposed into gravitational or inertial forces. How the nervous system extracts information from these two components to adjust the overall grip force level is not fully understood. The aim of this study was to assess the influence of the inertial component of torque load on object manipulation by performing experiments in weightlessness using an asymmetrical object. In Chapter 2, we demonstrated that the presence of a torque load on Earth slows down considerably the adaptation of Grip Force during static phases. However, in the laboratory condition, both gravitational and inertial components of loads are present. Therefore, performing the same experiment in weightlessness offers a unique opportunity to better understand the role of gravitational loads in this mechanism. Indeed, there are two possible hypotheses in this condition. The first hypothesis is that in weightlessness there will be no more difference in Grip Force adaptation between torque and no-torque load conditions; this would demonstrate that gravitational constraints are necessary to slow down adaptation in the torque load condition. The second hypothesis is that in weightlessness there will still be a difference in Grip Force adaptation between torque and no-torque load conditions, this would demonstrate that inertial constraints are sufficient by themselves to show the effect (a direct consequence being that gravitational constraints are not necessary). Removing the gravitational component of the torque load allows us to extract the impact of inertial torques during reaching on grip force adaptation. We investigated grip force adjustments during stationary holding under weightless conditions (when the tangential forces and torques equal 0) with or without an off-center mass attached to the manipulandum structure. Our results unambiguously favor the second hypothesis, as grip force adaptation under zero-g condition displayed strikingly similar properties as those observed under laboratory conditions (see Chapter 2), with similar adaptation rate that

was much slower than when no torque comes into play. Surprisingly, although the absolute levels of static grip force (sGF) were slowly adjusted across trials, we observed a clear dynamic modulation with the inertial components of tangential loads and torques indicative of a preserved ability to anticipate the consequences of movements. Altogether, our results quantify the importance of inertial constraints on both static and dynamic components of the grip force and highlight the importance of torque loads on the learning mechanisms and internal models adaptation during object manipulation.

3.2 Material and Methods

3.2.1 Subjects

Eighteen volunteers between 23 and 55 years old (17 right-handed and 1 left-handed) with no known neurological disorders gave their informed consent to take part in the experiment. Twelve subjects performed the main experiment and six subjects performed the control experiment. The subjects of the main experiment and the control experiment were different because we needed them to be naive to the purpose of the study and to microgravity conditions. They complied with the medical requirements to participate in parabolic flights (Belgian Center for Aerospace Medicine, class II medical examination). The experimental protocol was approved in terms of ethical and biomedical requirements for experimentation on human subjects by the European Space Agency (ESA) Medical Board Committee and the French Comité pour la Protection des Personnes, which reviews life science protocols in accordance with French law and the Helsinki protocols.

3.2.2 Parabolic Flight

The experiment was performed during the 55th, the 56th and the 59th ESA Parabolic Flight Campaigns on board of the A-300 0-G aircraft (Bordeaux-Mérignac, France). Parabolic maneuvers generated sequences of 20 s of hypergravity (1.8g), followed by about 22s of weightlessness (0g) before another period of 20s of hypergravity. Each participant per-

formed the task during a sequence of 30 consecutive parabolas. We monitored the gravity during the data acquisition and found that gravitational levels were relatively stable (average across blocks : $-0.003 \pm 0.0147g$; average standard deviation across blocks $0.0255 \pm 0.004g$). In the following sections, one block refers to the set of trials performed during one parabola. Each parabola was followed by a break of minimum two minutes.

3.2.3 Experimental Procedures

Main Experiment (TL condition)

Subjects sat in front of four LED targets vertically aligned with respect to the aircraft floor and separated by $10cm$. The program generated a random sequence of these LED targets at a frequency of $1Hz$. The target sequence was generated such that, at any time, the transition probability from the current target to any of the three remaining targets was equal to $1/3$. Subjects held a manipulandum with a precision grip (grip aperture $4.5cm$) and were instructed to align and stabilize it with the current LED until the next target was illuminated while minimizing rotational movements of the manipulandum induced by the presence of torque loads. They received the instruction to maintain the orientation of the manipulandum such that the off-centered mass stayed at the same height as their index and thumb fingers. Head, eye, and arm movements were not constrained. The subjects were allowed to manipulate the object only during the $0g$ phases to reduce clues regarding its mass as well as the torque load produced by the off-centered mass. A block of 17 point-to-point movements was performed during the $0g$ phase of each parabola. The manipulandum had a total mass of $340g$ including the off-centered mass of $40g$ placed at $10cm$ (Fig. 3.1). Between the trials, the subjects had to maintain the manipulandum on their left knee by holding it at the top with their left hand. The subjects could clearly see the off-centered mass but they had never held the manipulandum before the flight. Data acquisition began at the beginning of the $0g$ phase of each parabola (beginning of microgravity).

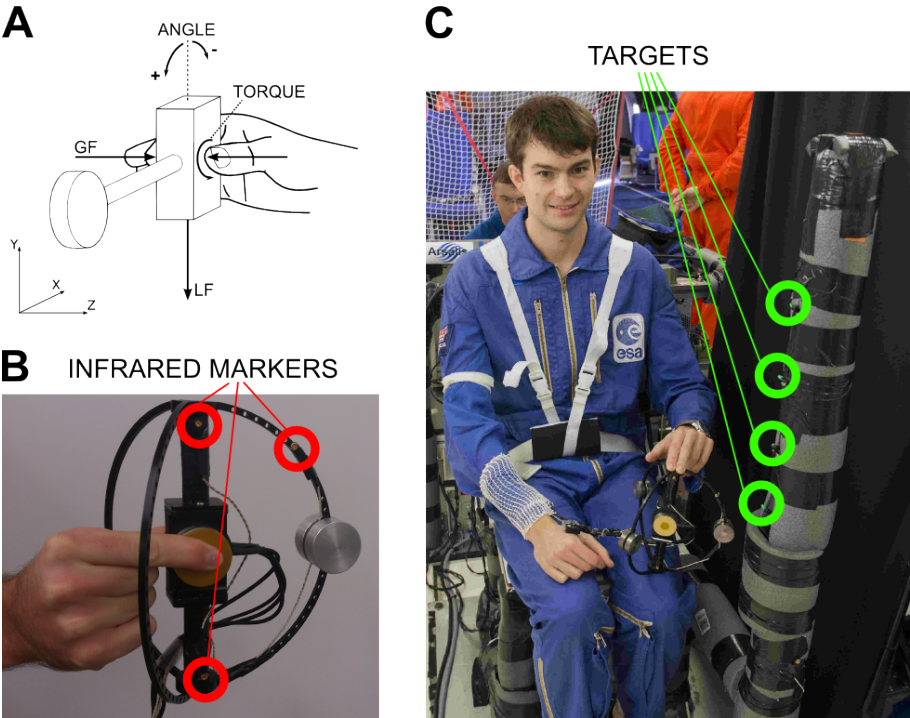


Figure 3.1: A: schematic representation of the instrumented object equipped with an off-centered mass that moved the center of mass away from the grip axis. The study focuses on the grip force (GF), the load force (LF), the torque load measured along the grip axis (T), and the rotation angle. B: photo of the manipulandum showing the off-center mass and position of the infrared markers used for motion tracking. C: picture of a subject before starting the first reaching movement. The manipulandum was held on participant's knee prior to reaching for the first target. The participant was maintained on the chair with two straps over the shoulders and one around the waist. The targets are depicted with four green circles.

Control Experiment (NoTL condition)

The control experiment, the task was exactly the same as the main experiment but the manipulandum was different. It was balanced with a total mass of 708g including three masses of 136g placed one on each hoop. This mass, called equivalent mass, was estimated based on a model of mechanical constraints to produce equivalent constraints and required the same level of GF for the same linear acceleration. We followed a theoretical approach based on the computation of the tensor of tangential constraints at the finger-object interface as in Chapter 2 (see Appendix B for more details). We computed the force density on the contact surface with and without the off-centered mass. On the basis of the hypothesis of linear addition, the force-density tensors corresponding to a centered mass only or a torque only were summed to estimate the overall force-density tensor. Then, we defined the equivalent mass as a centered mass, which would produce an identical integrated square norm of force density as the one computed in the presence of a torque. In such configuration, the integrated square norm of the force-density constraint at the fingertips is identical to the one in the main experiment for the same linear acceleration. With a such equivalence of constraints, the subjects produce similar levels of grip force in both conditions. Thus, it is possible to isolate the effect of the torque by comparing the main and the control experiment.

3.2.4 Apparatus and Data Collection

The custom manipulandum (ESAGLM, Arsalis, Louvain-la-Neuve, Belgium) was equipped with two three-dimensional force and torque sensors (mini 40 F/T transducers, ATI, Industrial Automation, NC, USA). We collected the tangential and normal forces at the interface between the fingers and the manipulandum, as well as the torque loads generated by the off-centered mass along the grip axis. The sampling rate for data acquisition of the sensors was 800Hz. Three-dimensional position signals of three infrared markers (infrared emitting diode [IRED]) placed on the manipulandum (see Fig. 3.1B) were sampled at 200Hz with a motion-tracking device (Codamotion System, Charnwoods Dynamics,

Leicestershire, UK).

3.2.5 Data Processing

From the position of the three infrared markers, we computed the location of the center of the spherical structure, corresponding to the center of the line segment joining the two sensors under the index and the thumb (Fig. 3.1). The vertical position and velocity of this point were considered. Regarding the rotation angle, the movements were first projected onto the plane orthogonal to the grip axis which allowed us to compute the angle from the change in orientation of the vector joining the center of the spherical structure to the off-centered mass. All position signals were digitally low-pass filtered with a zero phase-lag Butterworth filter of order four with a cut-off frequency of 20Hz. Let (F_{xr}, F_{yr}, F_{zr}) and (F_{xl}, F_{yl}, F_{zl}) be the force components measured on the right and the left sensors respectively and (T_{xr}, T_{yr}, T_{zr}) and (T_{xl}, T_{yl}, T_{zl}) be the torque components (Fig. 3.1A). The normal force applied on the manipulandum by the subject is called grip force (GF) and is defined as the mean of the components of the force normal to the surface of the object for both sensors.

$$GF = \frac{F_{zr} + F_{zl}}{2} \quad (3.1)$$

The baseline of GF exerted before each movement was measured during each static phase (stable manipulandum) and will be defined as sGF, the mean of GF in a window of 100ms beginning at target onset.

The difference between sGF of the first trial of a block b and the last trial of the same block b is called *sGF intra-block decrease* and represents the adaptation of the sGF during one block. The difference between sGF of the first trial of a block b and the last trial of the previous block $b-1$ is called *sGF inter-block wash-out* and represents the impact of the inter-block breaks on the level of sGF. The relative GF, rGF, is the difference between GF at a specific time during a movement and sGF measured before this movement.

$$rGF_j = GF(t_j) - sGF \quad (3.2)$$

The tangential force applied on the surface of the object is called the load force, LF (Fig. 3.1A), and is defined as the sum of the vertical component of the tangential forces, F_y , measured by both sensors. The torque load, T, is defined the same way as LF.

$$LF = F_{yr} + F_{yl} \quad (3.3)$$

Fig. 3.2 shows data from typical trials. It can be observed that there are two LF peaks during one movement. For an upward movement, the LF peak due to the acceleration is positive whereas the one due to the deceleration is negative and vice versa for a downward movement. During the movement, three specific times are defined : t_{LF1} is the time of the acceleration peak of LF, t_{LF2} is the time of the deceleration peak of LF and $t_{LF=0}$ is the time between t_{LF1} and t_{LF2} when the LF crosses zero. Three corresponding values rGF, were defined : $rGF_{LF=0}$ at $t_{LF=0}$, rGF_{LF1} at t_{LF1} and rGF_{LF2} at t_{LF2} . In the present study, it is not appropriate to compare the results of the two experiments on the basis of LF since only in the main experiment a torque load is present. Indeed, both linear and rotational tangential constraints must be taken into account. In our protocol, the main experiment and the control experiment were designed in such a way that the same linear acceleration produced the same integrated square norm of the force-density constraint at the fingertips in the two conditions (see Appendix B). Thus the linear vertical acceleration was the key parameter that was related to grip force in our data analysis. This implies that any torque due to rotational acceleration is not taken into account in this relationship. However, this approximation is reasonable since the torque induced by rotational acceleration represented less than $10 \pm 8\%$ of the total torque estimated based on the measured linear and rotational accelerations.

3.2.6 Statistical Analysis

We used two different statistical tests to analyze sGF. First, Student's t-test was used to test whether the mean sGF of the first three blocks differed significantly from the mean value of sGF for the last three blocks, i.e. to test for a decrease in sGF across blocks. Then, a negative expo-

nential, with the following equation :

$$sGF(n) = a_0 + a_1 e^{-a_2 n} \quad (3.4)$$

was used to characterize the average time course of sGF adaptation across blocks. To compare the rate of adaptation with and without torque, the time constant $1/a_2$ was compared between conditions. The significance of the difference between the means of the sGF inter-block washout was also established with Student's t-test. Deming regressions were used to compute the slopes of the correlation between rGF and acceleration as the slope of the relationship was very large and thus we observed a saturation of the classical least-square regression (**Cornbleet and Gochman**, 1979). A four-way mixed-design ANOVA was used to compare the slope (averaged on three consecutive blocks) of this correlation in the different conditions with direction of movement (up or down), acceleration or deceleration and block as independent within factors and load condition (TL or NoTL) as independent between factor.

3.3 Results

Typical traces from two consecutive movements, an upward movement followed by a downward movement, are illustrated on Fig. 3.2. The vertical dotted lines represent the target onsets and the gray zones represent the static phases. The horizontal dashed lines on the position plot are the positions of the four LED targets. At 0s, the LED target placed at 20cm was turned on. The subject, who was holding the manipulandum in front of the 10cm LED target, should have lift the manipulandum upward by 10cm but made an overshoot of about 2.5cm. At 1s, the target at 20cm was turned off and the 0cm target was turned on. The subject subsequently moved to the latter target.

A change in angle of $+7^\circ$ and -10° can be observed in this example for the upward and the downward movement, respectively. These rotations around the grip axis stayed very small during the whole experiment (mean : $8^\circ \pm 6^\circ$). These changes in angle were most likely induced by different postural configurations for each target and they had a limited

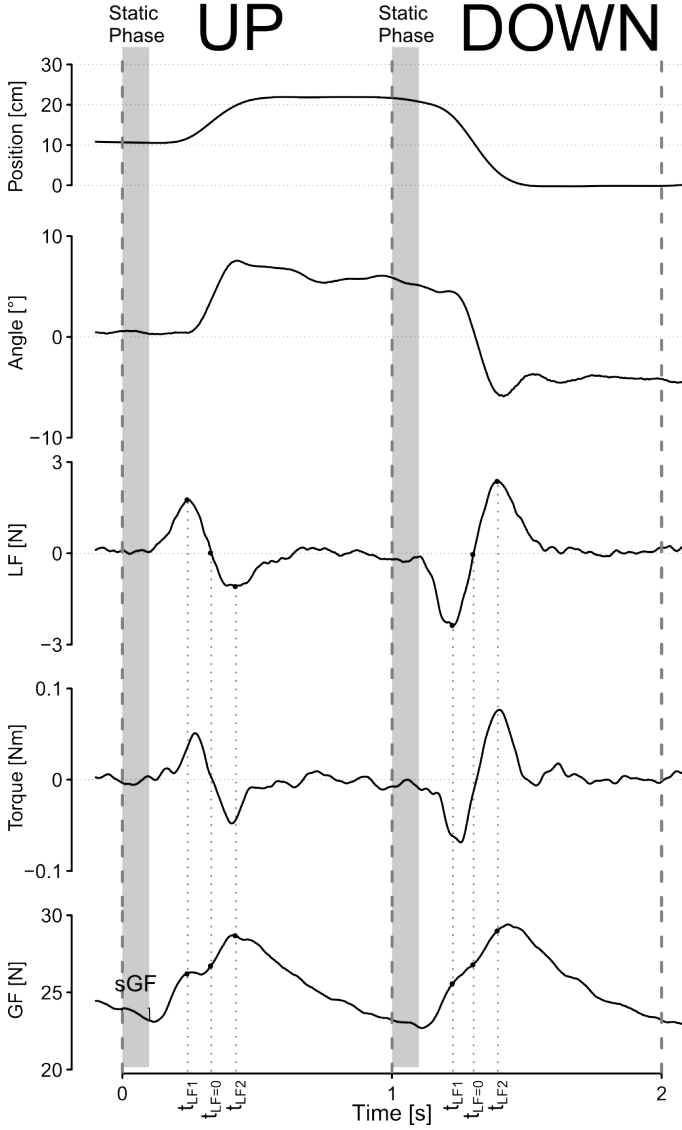


Figure 3.2: Typical traces of two consecutive movements (upward on the left and downward on the right, subject S1). The vertical dashed lines across all the panels represent target onsets. The gray zone are the static phases and sGF is averaged between brackets. Three important times were used for the analyses : t_{LF1} (first peak of LF or peak of acceleration), t_{LF2} (second peak of LF or peak of deceleration) and $t_{LF=0}$ (zero acceleration or zero LF between the two peaks of LF). On the position panel, the horizontal dotted lines represent the targets position.

influence on the torque load during the movement in comparison with the torque induced by the off-centered mass.

Indeed, the actual lever arm varies as the cosine of the changes in the joint angle, which represents a change of $< 5\%$ for angles comprised between -15 and 15 degrees. Furthermore, variations in effective gravity during parabola had also a limited impact on the torque level as the mean of standard deviation of the gravity level represented only 5% of the average acceleration peak during the movement.

Due to the microgravity condition, LF varied around $0N$ and depended only on the acceleration of the manipulandum. The peaks of LF occurred at the peak of acceleration and deceleration, t_{LF1} and at t_{LF2} respectively and LF passed by $0N$ at zero acceleration, $t_{LF=0}$ (vertical dotted lines).

The subject used a GF of $23.6N$ during the static phase before the upward movement and $23N$ before the downward movement. When the subject began the movement, the GF started to increase and kept increasing approximately until the second peak of LF. Then, it decreased to a lower level when the target was reached and the manipulandum was stabilized.

3.3.1 Static Component of GF

Fig. 3.3 illustrates the evolution of sGF across blocks, for one representative subject (S6) in panel A and for all subjects pooled together in panel B. Each square represents the mean sGF for all seventeen trials of the block (parabola). In Fig. 3.3A, the colored circles represent each individual trial. The black-red gradient shows the evolution within the block (black for the beginning and red for the end). Fig. 3.3A illustrates that sGF decreased with repetition across blocks for S6. Indeed, the average sGF of the three first blocks was significantly higher than the one of the three last blocks. This difference was significant for eleven out of twelve subjects (all except S12). At this point, it is already possible to state that the GF adaptation is still possible even without any gravitational torque load.

As the range of sGF across the subjects was large (TL : $13.20 \pm 5.38N$

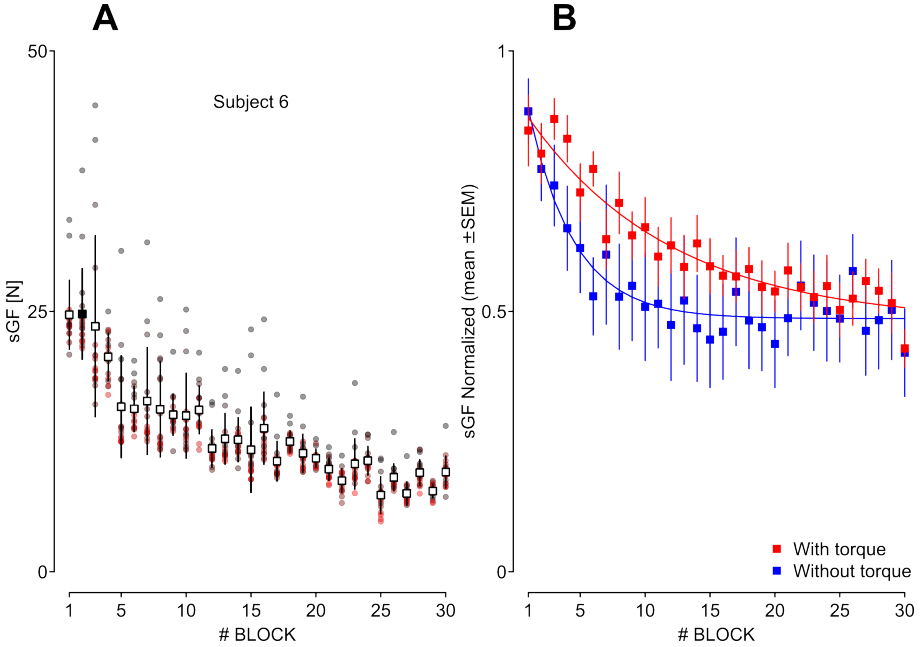


Figure 3.3: Evolution of sGF across blocks. A : Data of one representative subject (S6, main experiment). The squares are the mean of each block ($\pm$ SD) and the dots are the individual trials. The black square is the maximum of the means across all blocks and is used for the inter-subject normalization. The black to red gradient represents the evolution within the blocks (black = first trial, red = last trial). B : Evolution of the normalized sGF across blocks (mean across subjects $\pm$ SEM). The data collected during the main experiment are in red while the data collected during the control experiment without torque are in blue.

; NoTL : $12.56 \pm 4.88N$), the maximum of the mean of each block of each subject was used to normalize sGF before pooling the data across subjects in panel B. For subject S6, the maximum mean sGF corresponded to the mean sGF for block #2 and is indicated by the filled square in Fig. 3.3A. In the panel B, red corresponds to the data with torque load (TL) and blue to the data without torque load (NoTL). Fig. 3.3B clearly illustrates the significant decrease of sGF across blocks when all the subjects are pooled together (in red). We used the difference between the average sGF of the three first blocks and the average sGF of the three last blocks to quantify learning and found that it is about 33% in both conditions. The asymptotic performances are also similar across conditions: 41% in the TL condition and 51% in the NoTL condition. The comparison of the evolution of sGF in NoTL condition (in blue) shows how much the adaptation rate was influenced by the torque load in TL condition (in red). This observation can be quantified by the difference in time constant of the negative exponential fits in each condition which was more than three times shorter when no torque comes into play (time constant with torque : 11.11 blocks, 95% confidence interval : [7.74; 18.34] ; without torque 3.51 blocks, CI [2.64; 4.72]; R^2 : 0.89 in both conditions). Qualitatively, in TL condition, about 30 blocks were necessary before sGF stabilized in comparison with only 10 blocks in the NoTL condition. This exponential fit on individual data converged only for ten subjects out of twelve on the TL condition yielding an average time constant of 15.11 blocks and for five subjects out of six on the NoTL condition yielding an average time constant of 5.27 blocks. Thus, sGF adaptation was much slower in the TL condition even though there was no gravitational component to the torque load.

In addition to this slower adaptation across the blocks, we also observed a slower sGF adaptation across the trials within the blocks. Fig. 3.4 shows the mean ($\pm$ SEM) of normalized sGF across all subjects for all trials plotted across the blocks. The average decrease within blocks have been computed across the five first blocks as the difference in adaptation rate was mainly present during the beginning of the experiment. This average decrease within the blocks was 40% for the TL condition and 58% for the NoTL condition and was significantly differ-

ent between the conditions ($p = 0.01$). The effect on sGF adaptation across the blocks can not be explained by the difference in inter-block “washout” (increase between consecutive blocks) as the difference between the two conditions was not significant (washout : $NoTL = 48\%$ vs $TL = 37\%$, $p = 0.1$). Therefore, the slow down of sGF adaptation across the blocks reflected the same effect across trials due to the presence of the torque.

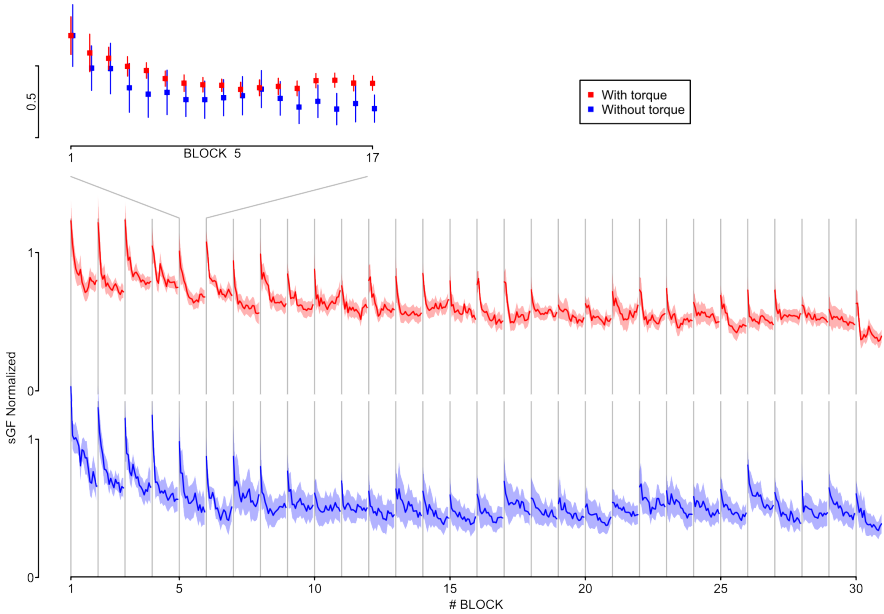


Figure 3.4: Evolution of the sGF across blocks detailed by trial. The thick lines are the means across subjects and the shaded surface represents the SEM. The gray lines are the beginning of each block. A zoom of the fifth block is shown at the top of the figure.

3.3.2 Dynamic Component of GF

We investigated if the presence of torque load had an impact on this GF modulation during the dynamic phase of the movement in comparison with the NoTL condition. To do so, we investigated whether the amplitude of rGF, change of GF with respect to sGF, scaled with the vertical acceleration in the same way in both conditions.

Fig. 3.5A shows this relationship for one subject (S11) in the TL

condition in the four cases (UP and DOWN, acceleration and deceleration peaks). On the panel B, the regression slopes of all subjects in both conditions are pooled together. There was neither a significant difference of slopes between conditions (TL versus NoTL), nor between the upward versus downward movements (condition : $F_{1,16} = 0.02$, $p = 0.88$; direction : $F_{1,16} = 0.51$, $p = 0.48$). Moreover, there was no significant difference across the blocks, meaning that, unlike sGF, the relationship between GF and acceleration stayed stable during the whole experiment (block : $F_{8,128} = 0.46$, $p = 0.53$).

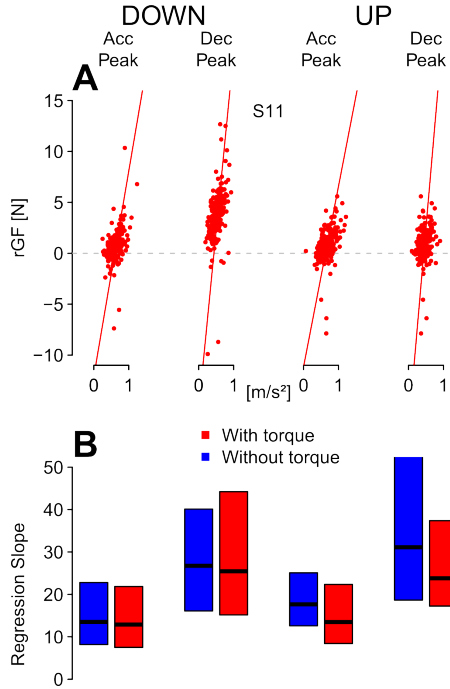


Figure 3.5: Correlation between the rGF and the Acceleration (absolute value). A : Exemplar subjects for all the movements (S11 for the TL condition and S4 for the NoTL condition). B : Boxplots of the regression slope for all the subjects pooled together. In the boxplots, the thick line represents the median and the box represents the interquartile range.

The correlation between rGF and the acceleration was significant in all conditions (acceleration and deceleration peaks, upward and downward movements, NoTL and TL) and for all subjects. This correlation was still significant when movements of one amplitude (between two ad-

jacent targets: 10cm) were considered separately. Hence, this correlation was not due to categorical changes in movement planning across different amplitudes, instead it reflects a fine coupling taking into account the subtle variation of movement kinematics across individual trials.

The lack of differences between the TL and the NoTL conditions in the dynamic phase supports not only that GF is still modulated even in presence of TL but also that TL is well estimated by the internal model dealing with GF modulation. Indeed, the fact that the slopes are not significantly different between TL and NoTL conditions suggests that the tangential and rotational constraints at the fingertips are taken into account and well estimated since these constraints are identical for the same acceleration in the two conditions (see methods, Section 3.2.3 and Appendix B).

3.4 Discussion

Our results show that despite a good and stable grip force modulation during the dynamic phase and a good correlation with the vertical acceleration, a slowing of the adaptation of the baseline of grip force is still induced by the presence of an inertial torque during object motion. Two important results will be discussed in this section. Firstly, the baseline level of sGF still decreased with repetition, even in presence of an off-centered mass but, more interestingly, the decrease was much slower than when no torque came into play. We also have shown that this difference in baseline of grip force adaptation rate reflected a difference in adaptation within the blocks as the inter-block washout was similar in the torque and no-torque condition. Secondly, the difference in static grip force adjustment rate is present despite qualitatively similar predictive grip force modulation during the dynamic phase, with or without torque experienced by the participants. Paradoxically, the inertial component of the torque load that only impacts the constraints during the dynamic phase of the movements seems to alter mostly the control of the baseline of grip force measured during the static phases.

3.4.1 Static Phase

In this study, we isolated the influence of the inertial torque on grip force adjustments and we showed that it is sufficient to slow down the adaptation of baseline grip force in comparison with the adaptation observed in the control experiment and in previous reports (Chapter 2 and **Crevecoeur et al.** (2009)). This result unmasks the specific role of the inertial part of TL, reproducing an effect already described in the literature during a repetitive grip-lift task in presence of both gravitational and inertial components of TL (see Chapter 2). This proves that the inertial torque load is sufficient to impact the adaptation of the baseline of grip force that is applied during the whole task but highlighted during the static phases, despite the fact that there is no gravitational or inertial load during stationary holding.

The GF washout between each block directly influences the GF adaptation rate. As we have shown, this inter-block washout was substantial and likely interfered with the overall adaptation observed across the parabolas. This washout effect has already been pointed out in the literature as a potential factor influencing short-term adaptation during parabolic flights (**Crevecoeur et al.**, 2010a,b). The present study clearly shows the presence of washout across parabolas, but it does not explain the slower adaptation rate observed in the presence of an off-centered mass. Indeed, we observed an overall slower decrease of the static grip force with torque, despite a smaller washout across blocks.

Note that the slowdown of baseline grip force cannot be explained by an effect of the weightlessness condition as the control and the main experiments were performed in microgravity. So, we can conclude that the difference in adaptation rate in presence of a torque was predominantly due to the inertial torques generated during the movements. In addition, it is interesting to note that the slow down of the adaptation between torque and no torque conditions was very large in the present study (time constant three times larger) and was of the same order of magnitude as in Chapter 2 (time constant four times larger) even though the experimental protocol and conditions were very different in the two studies. This shows that a dramatic increase in time constant might be

a general signature of adding a torque load in object manipulation.

3.4.2 Dynamic Phase

It is well established that there is a tight coupling between the GF and the LF when moving a grasped object (**Flanagan and Wing**, 1993, 1995; **Flanagan et al.**, 1993, 2006; **Flanagan and Tresilian**, 1994). This modulation, which is based on a predictive model, is also present in microgravity and hypergravity (**Hermisdörfer et al.**, 2000; **Augurelle et al.**, 2003a; **White et al.**, 2005; **Crevecoeur et al.**, 2009) as well as between the GF and the TL (**Wing and Lederman**, 1998). In this study, we confirmed that GF continues to be modulated as a function of the tangential loads even in the special case of weightlessness and even in the presence of an off-center mass. This was based on the observed tight coupling between GF and the vertical acceleration. Indeed, the tangential constraints can be estimated precisely from only the vertical acceleration if there is no rotation (see Chapter 2). The present experiment could not assess if the subjects modulated their GF based on an estimate of tangential constraints or directly from the vertical acceleration. However, based on the vertical acceleration, our analyses showed that grip force modulation was similar in the presence or absence of a torque load and that this modulation was stable from the first blocks.

Our results suggest that the modulation of grip force accounted for the presence of a torque. Indeed, the mass of the manipulandum differed across the experiments, which should have induced a difference in modulation gain if it were based on the net mass only (**White et al.**, 2005). The present experiment cannot assess whether participants were able to extract the specificity of rotational constraints induced by a torque from fingertip afferent or proprioceptive feedback. However, the similar gains across experiments suggest that the net amount of constraints, including the effect of the torque, was taken into account in the generation of anticipatory grip force modulations

Knowing the effect of the torque load on the baseline GF (described in Chapter 2), this result confirms the extension of the well-known phenomenon grip force modulation depending on the load-force to a more

general grip force modulation depending on the load-force and the torque load that takes into account both gravitational and inertial torque loads (**Kinoshita et al.**, 1997; **Goodwin et al.**, 1998).

3.5 Conclusions

We can make three important conclusions. First, the presence of an inertial torque is sufficient to slow down the adaptation of the baseline of grip force highlighted during stationary holding. Second, subjects are able to estimate rapidly and precisely the global constraints, including inertial torque, as demonstrated by the fact that GF/Acceleration modulation was similar whether a torque is present or not. And thirdly, as suggested in previous studies (see Chapter 2 and **Augurelle et al.** (2003a); **Crevecoeur et al.** (2009)), the difference of impact of the torque load depending on the grip force components suggests that the adaptation of the baseline grip force and relative grip force may be distinct processes with distinct learning capabilities. It remains to be demonstrated if these two processes are implemented by distinct or overlapping parts of the CNS or one unique complex mechanism.

Finally, it is important to mention that the sensorimotor adaptation of the grip force control during object manipulation is potentially a powerful tool for assessing learning capabilities in clinical as well as fundamental research. The slower adaptation due to the torque load allows assessing more precisely the learning capabilities. This adaptation measurement could be useful for clinical diagnostics or rehabilitation monitoring for example. The presence of an off-centered mass inducing a torque load provides an easy and effective way to investigate grip force adjustments because it slows down the adaptation rate and makes learning mechanisms more apparent (see Chapter 2). Thus this study is important since it helps better understanding the mechanisms of the slower grip force adaptation in the presence of a torque.

Chapter 4

Load torque discrimination is better during passive stimulation than active grip-lift¹

Abstract

Sensory inputs help us to get information about object properties. The grip-force control is partially based on this internal representation of the object. Previous studies reported a slow down of grip-force adaptation when manipulating an unbalanced object. However, the origin of this effect is still unclear. One possible explanation could be a poor ability to discriminate two distinct load torques which would imply an inaccurate internal representation of the object and impact the grip-force control. In this paper, we report the results from three experiments in which subjects were required to discriminate load torque during one active grip-lift task and two passive finger stimulation tasks. Subjects had to report which of two torque stimuli presented was the largest. The active grip-lift task results showed that in the tested $\Delta Torque$ range (0 to 20mNm)

¹Giard, T., Crevecoeur, F., Thonnard, J.-L., Lefèvre, P. (2015), Load torque discrimination is better during passive stimulation than active grip-lift. (In preparation)

the discrimination rate never surpassed 70%. Surprisingly, the subjects were much better during the passive tasks reaching 75% of discrimination from a $\Delta Torque$ of $5mNm$. These results show that the context of the task has a strong impact on the load torque discrimination. Indeed, the active task deteriorates the load torque discrimination performance.

4.1 Introduction

Manipulating an object, one uses touch, proprioceptive and vision inputs to estimate its properties (**Dodson et al.**, 1998; **Goodwin et al.**, 1998; **Jenmalm and Johansson**, 1997; **Wheat et al.**, 2004). The consciousness of the state of the arm, hand and fingers also provides valuable information, for instance for weight estimation (**Bell and Shaw**, 1834). These sensory inputs are even enhanced during a voluntary movement (**Brodie and Ross**, 1984; **Weber et al.**, 1996). Indeed, the descending motor commands and their consequences on the kinematics and the dynamics of the movement are interpreted to extract additional information about the object. Previous studies have shown that this additional information is used to improve weight and force perception (**Bell and Shaw**, 1834; **Brodie and Ross**, 1984; **Weber**, 1978).

The actions that we perform have a major impact on the perception of our environment. This impact can be inhibitory. For instance, visual perception is dramatically reduced during rapid saccadic eye movements (**Judge et al.**, 1980; **Volkmann et al.**, 1968). It has also been shown that a self-generated stimulus is perceived as less intense than the same stimulus generated externally (**Bays et al.**, 2006; **Blakemore et al.**, 1998, 1999; **Creutzfeldt et al.**, 1989). Actions can also provide additional sensory information as mentioned above in the example of voluntary movements that improve weight perception (**Bell and Shaw**, 1834; **Brodie and Ross**, 1984; **Weber**, 1978).

We can easily be exposed to load torques when we manipulate an object. Even if we generally try avoiding this situation (**Lederman and Wing**, 2003; **Lukos et al.**, 2007), the object can be taken away from its center of mass, for instance because of an unexpected mass distribution. Importantly, we are able to adjust our grip force depending not only

on tangential load forces (**Flanagan and Tresilian**, 1994; **Flanagan and Wing**, 1993, 1995, 1997b; **Johansson and Westling**, 1988a,b) but also on load torques (**Goodwin et al.**, 1998; **Johansson et al.**, 1999; **Kinoshita et al.**, 1997; **Wing and Lederman**, 1998). However, if there is experimental evidence for a good performance in discriminating efficiently normal and tangential forces (**Paré et al.**, 2002; **Wheat et al.**, 2004), little is known about load torque discrimination and our ability to discriminate distinct load torques.

In the present study, we address the impact of an active manipulation on load torque perception in comparison with a passive stimulation. We first show a poor ability to discriminate load torque during an active grip-lift task. Comparing, this result with passive stimulations, we demonstrate that load torque discrimination is dramatically deteriorated by the active manipulation itself.

4.2 Material and Methods

4.2.1 Subjects

Thirty healthy subjects participated in this study after giving informed consent (12 females and 18 males, all right handed). The experimental protocol was approved by the Ethics Committee of the Université catholique de Louvain (Belgium). They were divided into three different groups corresponding to three different experiments described below. Their age ranged from 23 to 45 years old.

4.2.2 Procedure

In the three experiments, we used a two alternative forced choice. The subjects performed three blocks of ten trials. Each trial consisted of two stimuli in which distinct load torques were applied. The load torques were produced either by the subject himself by gripping, lifting and holding an unbalanced object (active manipulation, Experiment 1) or imposed on the fingertip by a robotic platform (passive manipulation, Experiments 2 and 3). During each trial, two load torque stimuli were presented to the subjects. At the end of each trial, they had to report to

the experimenter which load torque stimulus was the largest (Fig. 4.1A).

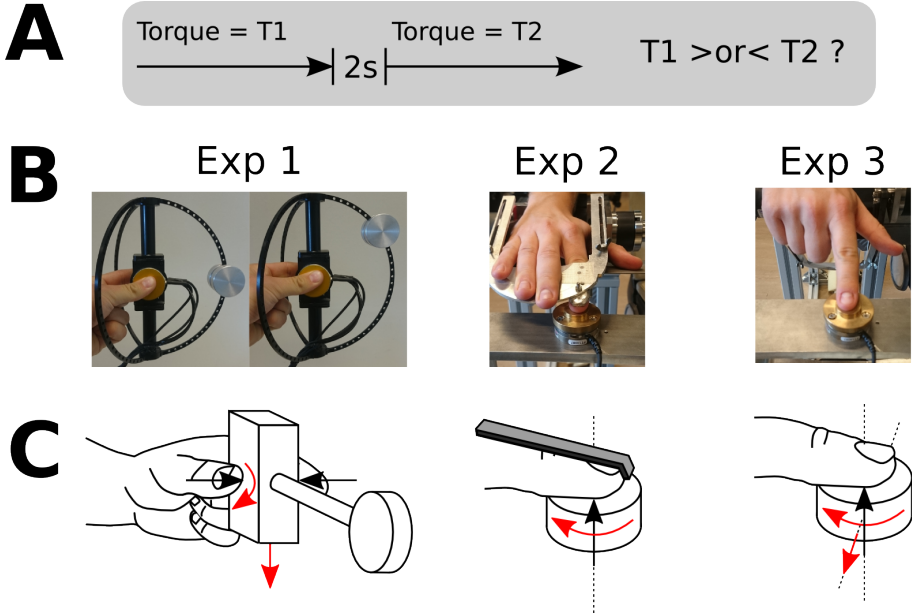


Figure 4.1: A : Time course of one trial. In the three experiments, a trial started with the presentation of the first load torque T_1 followed by a short break of 2 seconds and then ended by the presentation of the second stimulus. At the end of each trial, the subjects had to report which load torque was the largest. B : For each experiment, a picture shows the corresponding setup. For Experiment 1, the picture shows both manipulanda with the off-centered mass at 0° on the left and 45° on the right. On the picture of Experiment 2, the subject's finger and hand are fixed on a support. The finger is placed on the force and torque sensor which is covered with brass. On the picture of Experiment 3, the subject's finger and hand are free and the subject pushes actively on the force sensor which is covered with brass as in Experiment 2. C : A schematic representation of the normal force (black arrows) and the loads (red arrows) applied during each experiment.

Experiment 1

In Experiment 1, subjects ($N = 10$) performed a grip-lift task with manipulanda presenting an off-centered mass. Two manipulanda with different load torques but with the same mass were used for this active task (Fig. 4.1B, EXP 1, left column). The subject was blindfolded

and sat with the hands on the knees in front of a table on which both manipulanda were placed vertically. The subject was guided by the experimenter to grasp the first manipulandum with the thumb and the index finger of the right hand and lift it up for about five seconds avoiding any slipping and tilting. Then, he/she put it down on the table, grasped the other manipulandum helped by the experimenter and lifted it up, also for about five seconds. At the end of each trial, the subject reported which load torque stimulus was the largest. Before the first trial, each subject performed a practice trial without being blindfolded to be sure that he/she had fully understood the instructions.

Experiment 2

The goal of this experiment was to assess of the load torque discrimination threshold when only the fingertip was stimulated by a pure torque. The subjects ($N = 10$) performed a passive task in which only a load torque and no translational force was present. In this task, we used a robotic platform to apply a load torque on participants' index fingertip while their hand was fixed on a support (Fig. 4.1B and C, EXP 2, central column).

The subject was blindfolded and sat beside the robot with the hand on the support and the index finger (right hand) just above the sensor without touching it. During each trial, the subject compared two load torques, the test load torque and the reference load torque. The reference and the test stimuli were presented to the subject in a random order separated by a 2 seconds break. A normal force of $35N$ was applied on the fingertip prior to each torque stimulus. The subject reported to the experimenter which of both torque stimuli was the largest. No practice trial was needed for this experiment. Indeed, the load torque was well controlled by the robot and the first $\Delta Torque$ presented was high enough to feel easily the difference between both stimuli and understand the instructions.

The reference load torque was $20mNm$ (millinewton meter) whereas the test load torque varied in an adaptive way in a range starting from $40mNm$ to $21mNm$ divided into eight levels (40, 35, 30, 28, 26, 24, 22

and $21mNm$). Using a standard psychometric approach (**Jones and Tan**, 2013; **Leek**, 2001; **Zwislocki and Relkin**, 2001), the test load torque was adapted according to participants' answer as follows: in each test torque level, after two correct answers, any following correct answer at this level induced a test load torque decrease, even if the correct answers were not consecutive; after every incorrect answer, the test load torque increased. It has been shown that using this adaptive method, the test stimulus stabilization is around a discrimination threshold of 75% (**Libouton et al.**, 2010; **Zwislocki and Relkin**, 2001). We considered that the test stimulus was stable after three reversals in a single level being defined as an incorrect answer immediately followed by a correct answer (**Kaernbach**, 2001). We defined the threshold window as the period between the first answer of the first reversal (incorrect answer) and the second answer of the third reversal (correct answer). Finally, the stabilization level and thus the 75% discrimination threshold were defined as the mean of all the $\Delta Torque$ of all the trials within the threshold window.

Experiment 3

This experiment addressed whether the absence of tangential force and the passive application of the normal force facilitated the discrimination during Experiment 2 in comparison with Experiment 1. Thus, Experiment 3 was similar to Experiment 2, with the difference that participants ($N = 10$) pushed actively on the platform. In addition, a tangential load was applied to match the load constraints measured in Experiment 1 (Fig. 4.1C, EXP 3, right column). The hand was not fixed on a support (Fig. 4.1B, EXP 3, right column) and the robot controlled and maintained the normal force level at $15N$. This level of normal force has been chosen to be as close as possible to the average grip force used by the subjects in Experiment 1 while avoiding slipping.

4.2.3 Apparatus

Experiment 1

Two custom manipulanda (ESAGLM, Arsalis, Louvain-la-Neuve, Belgium) were equipped with two three-dimensional force and torque sensors with a diameter of 45mm (mini 40 F/T transducers, ATI, Industrial Automation, NC, USA). We collected the tangential and normal forces at the interface between the fingers and the manipulandum, as well as the load torques generated by the off-centered mass along the grip axis. The sampling rate for data acquisition of the sensors was 800Hz . Both manipulanda were equipped with three 10cm radius hoops on which off-centered masses could be placed at different angles (Fig. 4.1B, EXP 1, left column). A 70g mass was added on the central hoop at 0° on one manipulandum and at 45° on the other one. Thus, both manipulanda had the same total mass of 370g but generated two different load torques, respectively 35mNm and 25mNm on the index finger. The theoretical load torque difference was then 10mNm . Note that the subjects were blindfolded, so the grasp was not always exactly centered on the sensors. This variation of fingers position on the sensors could increase or decrease the load torque as a result of change of lever arm. In addition, the manipulandum was not always lifted perfectly vertical and this tilted grasp also induced small changes in load torque. The tilt and the fingers position induced a variability of the load torques and thus a variability of the ΔTorque . For instance, a change in position of 10mm induced a change in load torque of 7mNm . However, we used this variability as an advantage to assess the torque discrimination on a wider ΔTorque range.

Experiment 2 and 3

For these experiments, a 4-axis industrial robot (DENSO HS-4535G) was used. Its position was controlled with a resolution of $15\mu\text{m}$ at a frequency of 1kHz . The robot was instrumented with a 3-D force and torque sensor (Mini40 Force/Torque transducer, ATI Industrial Automation, Apex, NC, USA) that provided measures of normal force, tangential forces and load torque applied on the finger. The transducer was cov-

ered with brass and was fixed horizontally on a metal plate (Fig. 4.1B, EXP 2 and EXP 3, central and right column respectively) attached by the robot. The subject's index finger was fixed during Experiment 2 and free during Experiment 3. The sampling rate for data acquisition of the sensor was $1kHz$.

4.2.4 Data Processing

For all the experiments, the load torque LT was defined as the normal component of the torque measured by the sensor under the index finger (right sensor for Experiment 1).

In all the experiments, the reference torque T_{ref} and the test torque T_{test} were the value of the LT plateau of the lowest stimulus and the highest stimulus respectively (Fig. 4.2, top row). In Experiment 1, we defined T_{ref} and T_{test} as the mean of LT during the last second before the subject moved down the manipulandum. We considered that the downward movement begins when $|\frac{dLF}{dt}| > 0.1$ N/s. In experiments 2 and 3, we defined T_{ref} and T_{test} as the mean of TL during one second period starting 1.5s before the normal force dropped down to 0. Then, we defined the difference between both stimuli, $\Delta Torque$, as follows:

$$\Delta Torque = T_{test} - T_{ref} \quad (4.1)$$

We divided the $\Delta Torque$ range into five bins in order to analyze the evolution of correct answers percentage. The bins were chosen in order to equally distribute the total number of trials across the bins. So, each bin contains 60 trials in each experiment. The correct answers percentage has been computed for each bin and each subject and then averaged across the subjects for each experiment. These bin average percentages have been used for Fig. 4.4. Following standard models (Buracas et al., 2005; de Balthasar et al., 2008; Dobkins et al., 2006), we fitted the following Weibull function on participants' data with two variable parameters (b and t):

$$y = 1 - (1 - g)e^{-\left(\frac{kx}{t}\right)^b} \quad (4.2)$$

where

$$k = -\log \left(\frac{(1-a)}{(1-g)} \right)^{\frac{1}{b}} \quad (4.3)$$

y is the correct answers percentage, x is the $\Delta Torque$ average of the bin, b is the shape parameter of the function, g is the performance expected at chance, a is the performance level that defines the threshold t . That is, if $x = t$, then $y = a$. In our case, $g = 50\%$ (two alternative forced choice) and we defined $a = 75\%$ to be able to confirm the threshold obtained with the adaptive method (see above). The least squares error optimization was used to determine the two variable parameters, b and t .

For Experiment 1, we defined ΔGF as the difference of grip force used during both stimuli:

$$\Delta GF = GF_{test} - GF_{ref} \quad (4.4)$$

A negative ΔGF is then possible and means that the grip force used for the test stimulus (large torque) is smaller than the grip force used for the reference stimulus (small torque). We divided ΔGF range into three bins in order to analyze the influence of the ΔGF level on the performances. The first bin ($n = 70$) includes all the trials with a ΔGF smaller than $-1N$. The second bin ($n = 70$) includes all the trials with a ΔGF between $-1N$ and $1N$ (34 trials with a negative ΔGF). The third bin includes all the trials with a ΔGF larger than $1N$.

4.2.5 Statistical Analysis

We used a mixed ANOVA to investigate how the percentage of correct answers varies across the bins (within factor) and across experiments (between factor). Then, a Tukey's test was used as post-hoc analysis to detail the results of the mixed ANOVA. We also performed one-way ANOVA to assess how the percentage of correct answers varies across the bin within each experiment and depending on the experiment within each bin.

4.3 Results

Fig. 4.2 shows the temporal evolution of reference and test stimuli of one representative trial for each experiment. The test torques, T_{test} , and the reference torques, T_{ref} , are the average torque for the zone depicted in the square brackets. On these selected examples the difference between the test and the reference torque was about $10mNm$ (double arrows on Fig. 4.2). For both stimuli of Experiment 1, the load force stabilized around $1.85N$ (Fig. 4.2) which corresponds to half of manipulanda weight, as their total weight ($3.7N$) was distributed between the index finger and the thumb. In the case of Experiment 2, for both stimuli, the load force was close to zero (Fig. 4.2). Indeed, it stabilized at $0.17N$ and $0.11N$ for the test stimulus and the reference stimulus respectively. Finally, for Experiment 3, for both stimuli, the load force got around $1.85N$ (Fig. 4.2), which corresponds to the tangential force applied on the index finger during Experiment 1.

The $\Delta Torque$ evolution across the trials of one representative subject of each experiment is shown on Fig. 4.3. The open and filled disks depict the correct and the incorrect answers respectively. The $\Delta Torques$ of Experiment 1 vary between 0 and $25mNm$ (see Section 4.2.3 for more details on this variability). The method used for Experiment 2 (see methods) is well illustrated on Fig. 4.3. Indeed, the first $\Delta Torque$ decrease can be observed between the third and the fourth trial and the first increase can be observed between the fourth and the fifth trial. The threshold window is delimited by the ninetieth trial and the twenty-third trial. The threshold (dashed line) is the mean of all the $\Delta Torque$ contained in the threshold window and is equal to $5.2mNm$ for this particular subject. The average threshold across subjects is $4.25 \pm 0.78mNm$ (mean $\pm$ SEM). Regarding Experiment 3, it can be observed on Fig. 4.3 that the different levels of $\Delta Torque$ are not well separated as in Experiment 2. Indeed, the load torques were more variable than in Experiment 2 because the hand was not attached, the subject had to push actively on the platform, and an additional translational force was present. However, we can already observe that the incorrect answers are less present and in a much lower range than in Experiment 1.

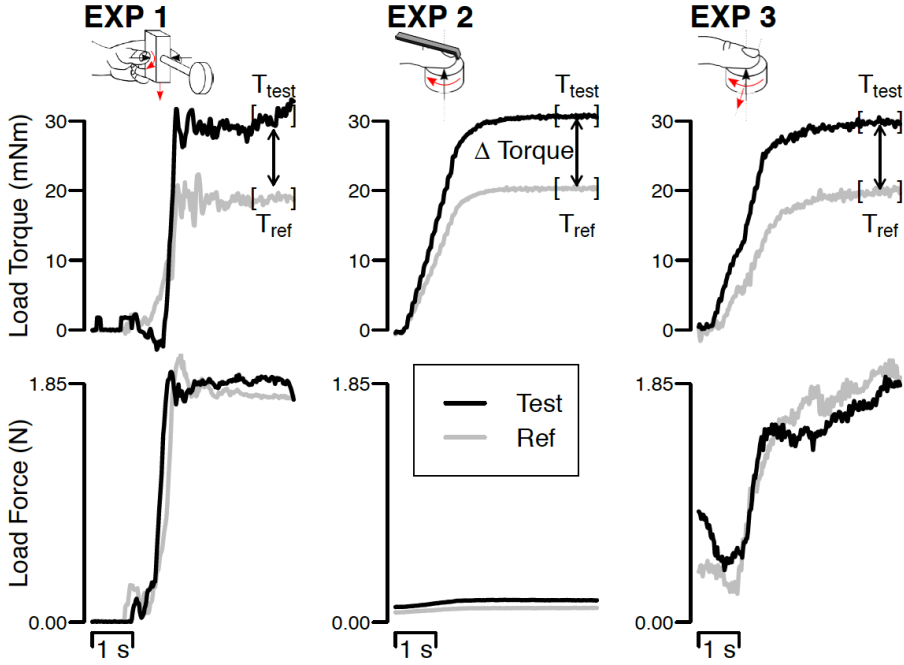


Figure 4.2: Representative traces of the reference and test load torque and the corresponding load force of one trial for each experiment. The black lines and the gray lines stand for the test and the reference stimuli respectively. The T_{test} and the T_{ref} are defined as the average torque between the square brackets and the double arrow represents the $\Delta Torque$.

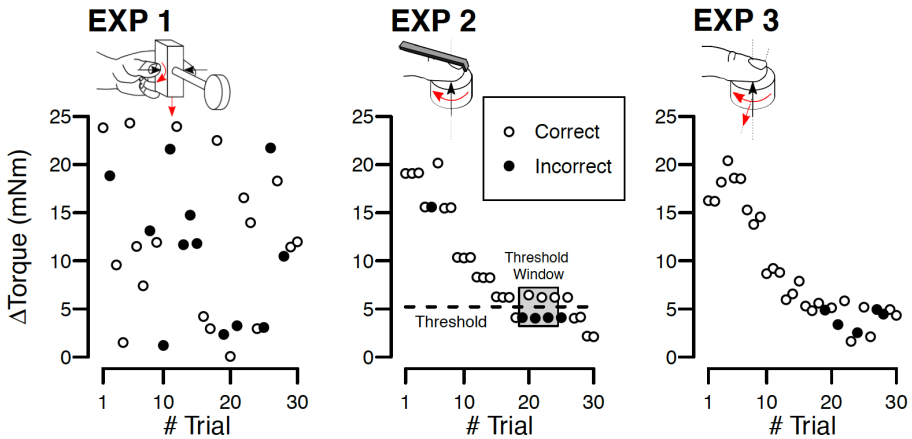


Figure 4.3: $\Delta Torques$ of one representative subject for each experiment. The empty and filled disks depict the correct and the incorrect answers respectively. For the experiment, the gray rectangle is the threshold window while the dashed line is the 75% threshold.

To compare the discrimination performances of the three experiments, the correct answers percentage was computed for five bins, for each experiment (see methods) and plotted on Fig. 4.4. For the lowest $\Delta Torque$ bin, the correct answers percentages were the lowest of the five bins in the three experiments. For the bin which is the closest to $20mNm$, the performance was close to 100% of correct answers in the passive stimulation experiments (2 and 3) but only reached 71% of correct answers for the active grip-lift task (Experiment 1). The lines on Fig. 4.4 are the Weibull functions (see methods) fitted on the data of each experiment. The shape parameter, b , is equal to 0.02, 0.027 and 0.032 for Experiment 1, 2 and 3 respectively. The threshold parameter, which is an estimation of the minimum $\Delta Torque$ necessary to reach a load torque discrimination of 75%, is equal to $22.7mNm$ (Weber fraction of 0.64) for Experiment 1 while it is more than four times lower for Experiment 2 and 3 ($5.5mNm$ and $5.7mNm$, Weber fraction of 0.28) respectively. Note that the threshold of Experiment 2 computed by means of the Weibull function is consistent with the threshold found thanks to the adaptive method (see description of Fig. 4.3). This similarity between the two methods in Experiment 2 emphasizes that estimates of discrimination thresholds based on fitting of a Weibull function is consistent with the adaptive approach.

For all bins together, the experiment type has a highly significant effect ($p < 10^{-4}$) on the correct answers percentage (mixed ANOVA, see methods). The latter is significantly different between Experiment 1 and the two other experiments (Tukey's test, $p < 10^{-4}$) but this difference is not significant between Experiment 2 and 3 ($p = 0.97$). As it can be easily observed on Fig. 4.4, the performance difference between Experiments 2 and 3 and Experiment 1 is significant from the third bins (one-way ANOVA on each bin, see methods). For all experiments together, the increase in percentage of correct answers across the bins is also highly significant ($p < 10^{-4}$, mixed ANOVA). However, in Experiment 1, the proportion of correct answers did not vary significantly across bins ($p = 0.38$).

In Experiment 1, the grip force was produced by the subject himself in order to lift the object without letting it slip. In Fig. 4.5, the

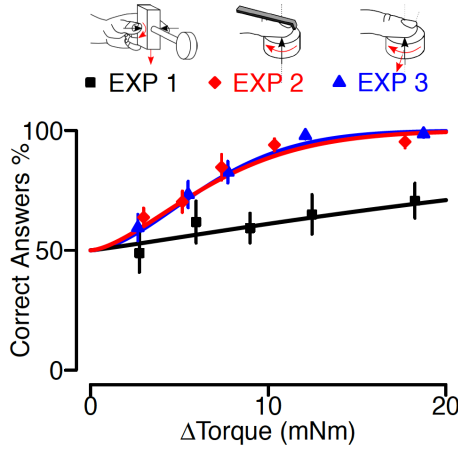


Figure 4.4: The correct answers percentage in function of the ΔTorque grouped by bins (see Section 4.2.4). The vertical segments are the standard errors of the mean and the solid lines are the Weibull function fits.

performances of Experiment 1 are clustered into three levels of ΔGF . As specified in the Methods, a negative ΔGF means that the smallest grip force has been used for the largest torque between both stimuli. When ΔGF is greater than 1 the correct answers percentage is around 75% while when ΔGF is smaller than $-1N$ it is around 25%. The third ΔGF level is close to 0 (between $-1N$ and $1N$). In this case, the performance is clearly close to the positive ΔGF . The level of ΔTorque has no significant influence ($p > 0.65$) within any ΔGF level.

4.4 Discussion

With the three experiments reported in this paper, we have shown that our performance to discriminate load torques is influenced by the nature of the task performed. The 75% threshold of load torques discrimination during a passive stimulation is more than four times lower than during an active grip-lift task. The results of Experiment 1 showed that, during an active grip-lift, the threshold of 75% of correct answers should be around $22mNm$. In contrast, the results of Experiment 2 showed that the load torque discrimination during a passive stimulation already reaches the

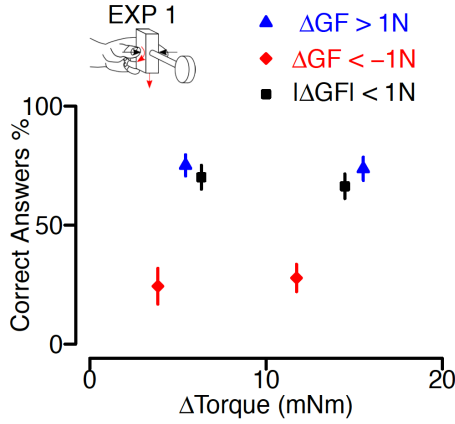


Figure 4.5: The correct answers percentage of Experiment 1 in function of the $\Delta Torque$ grouped by ΔGF magnitude and separated in two bins of $\Delta Torque$ of equal size. The vertical segments are the standard errors of the mean.

75% threshold around $5mNm$.

The results of Experiment 3 demonstrated that a passive stimulation combining load torque and load force produced a discrimination performance similar to passive stimulation with pure load torque. Indeed, the presence of a translation force, namely the manipulandum weight, during Experiment 1 could have explained this difference in performance with Experiment 2. The goal of Experiment 2 was to provide an estimation of the discrimination threshold when the fingertip was stimulated with a pure torque. The absence of load force could have been the origin of the difference between Experiment 1 and 2 following the idea of Weber's law (**Pang et al.**, 1991; **Weber**, 1978). Indeed, when we grasp an object away from the center of mass and lift it up, the finger tips are stimulated in rotation by a load torque but also in translation by the object weight. The local shear stresses due to the object weight all point in the same direction, which is not the case for the local shear stresses due to the pure torsion. So, the directional organization of the shear stresses is strongly influenced by the object weight. Then, it could be hypothesized that the ability to discriminate load torque is limited by the presence of this translational force. Experiment 3 discarded this hypothesis by adding a translational force to the passive fingertip stim-

ulation. The difference in normal force between Experiment 1 and 2 can neither explain the discrimination difference as the normal force used during Experiment 2 was similar to the grip force produced by the subject during Experiment 1. Our results showed that the performance of the passive fingertip stimulation in presence of a translational force is also much better than during the active grip-lift task.

This better discrimination performance during passive stimulation was unexpected. It has been shown that even if the weight or force discrimination is precise with touch alone, it is better if the object is actively lifted (**Flanagan and Wing**, 1997a; **Jones**, 1986). The effect seems to be inverted for load torque discrimination according to our results. Moreover, **Jones** reported that the perception obviously improves when there are more sources of sensory information. It also has been shown in the literature that combining the cues coming from different modalities, the estimation of the properties of the object should be better (**Angelaki et al.**, 2009; **Ernst and Banks**, 2002; **van Beers et al.**, 1999). In Experiment 1, the two main sensory sources are the tactile feedback coming from the fingertips and the proprioceptive feedback coming from all the muscles, the tendons and joints of the fingers, the hand and the arm. In contrast, in Experiment 2, the proprioceptive feedback is drastically reduced and the sensory information mostly comes from the tactile feedback of only one finger. Surprisingly, our results showed that load torque discrimination is easier during passive stimulation with less sensory cues than during an active grip-lift task.

The movement gating of tactile sensations could explain this unexpected result (**Bays et al.**, 2006; **Cullen**, 2004; **Post et al.**, 1994; **Schmidt et al.**, 1990). It has been demonstrated on one hand, that the detection of tactile stimuli is attenuated during movement and on the other hand that self-generated tactile stimulations produced a decrease in tactile detection. In the context of a grip-lift task, the sensory gating during weight discrimination could be compensated by the redundancy of the tactile and the proprioception feedback. This could explain why better weight discrimination is observed during active task despite the sensory attenuation. However, in the case of load torque perception, tactile and proprioceptive information are not redundant but comple-

mentary. Indeed, it is possible to produce exactly the same torque at a particular finger or hand joint with different object configurations, which is not the case with balanced objects. It can be hypothesized that the number of afferent information sources is not sufficient to compensate for voluntary movement gating of sensory feedback in the context of active grip-lift load torque discrimination. So, this sensory gating could produce a stronger effect on load torque discrimination than on weight discrimination during an active grip-lift and could be the reason why we observed a better performance during the passive tasks.

Another hypothesis would be that the subject's answers during active grip-lift task are based on the grip force comparison instead of torque comparison. Thus, when the difference in grip force is in opposition to the difference in torque, the performance drastically drops (see Fig.4.5). However, when this difference in grip force gets close to zero, the subject uses the tactile and proprioceptive feedbacks which would explain the gap in performance between a negative ΔGF and a ΔGF around 0.

Our results showed a poor load torque discrimination ability which could explain why grip force adjustments when we manipulate unbalanced objects is appreciably slower (see Chapter 2 and 3). This effect could be explained, at least partially, by a worse ability to discriminate load torques than tangential forces. Indeed, it has been shown that it is still possible to efficiently discriminate tangential force at a Weber fraction around 10% (Paré et al., 2002) while we showed that for load torque discrimination the Weber's fraction was about 25% and 64% at 75% performance threshold for the passive and the active stimulation respectively. Moreover, the sensory information related to the load torque is even worse during active manipulation.

4.5 Conclusion

In this study, we have shown that the load torque discrimination depends on the context of the task. Although future studies have to be conducted to explain this performance difference, it already supports the hypothesis that the poor load torque discrimination ability during active task could partially explain the load torque effect on the grip-force

adaptation during unbalanced object manipulation.

Chapter 5

General Conclusions

The main contributions of this thesis are summarized in the first section (5.1) of this chapter. The second section (5.2) proposes a global discussion about previous chapters based on the load torque literature (1.5). Finally, the limitations and the possible perspectives of this work are presented in the last section (5.3).

5.1 Main Contributions

Although load torques are frequently present during object manipulation, load torque influence on grip force control is still not fully understood. Previous studies (described in Section 1.5) demonstrated that load torques are taken into account in the grip force modulation (**Goodwin et al.**, 1998; **Kinoshita et al.**, 1997; **Wing and Lederman**, 1998). The goal of this thesis was to bring new elements to the global understanding of the grip force control in the particular context of the manipulation of unbalanced object inducing load torques. The studies conducted are based on the background described in the introduction (see section 1) and especially on the load torque section (1.5).

We first showed (see Chapter 2) that the mechanism of grip force adaptation is deeply impacted by the presence of a load torque. During a repetitive grip-lift task, the grip force used to hold the object tends to decrease until a stabilization level. The presence of a load torque drastically slows down the rate of this grip force adjustment.

In the second study (see Chapter 3), we demonstrated that the dynamic load torques produced by movements are sufficient to disturb the adaptive control of grip force. It has also been showed that the grip force controller processes a combination of the load torques and load forces to regulate the grip force. Indeed, the magnitude of the grip force modulation with global load variation (torques and forces combined) is similar as with load force alone.

Finally, we established that active lifts degrades the load torque perception (see Chapter 4). The load torque discrimination during passive fingertip stimulation is really precise. Indeed, in the passive condition, the 75% threshold of load torque discrimination was reached for a difference of $5mNm$. But, during the active grip-lift task, the performance was strongly deteriorated. The slow grip force adaptation showed in the previous studies could be explained by this poor load torque discrimination.

5.2 Discussion

Slow grip force adaptation in presence of load torque might only be the consequence of an ineffective programming of grip force baseline¹. Inhibition or disturbance of afferents and inefficient use of sensory information could be the cause.

The scaling between the grip force baseline and load torque could be inaccurate when based only on tactile and/proprioceptive feedback. Indeed, it has not been formally demonstrated that this scaling is possible when no visual cues about the center of mass are present. During the experiment described in **Kinoshita et al.** (1997), the correlation between the grip force and the load torque during the static phase might be a direct consequence of the experiment design (see Section 1.5 for more details). The subject was instructed to decrease the grip force level and let the object rotate. This rotation induced a reduction of load torque by reducing the moment arm. So, the grip force was not actively scaled

¹The grip force baseline is defined as the level of grip force used during static phases of the object manipulation (see Section 3.2). The grip force modulates around this baseline during dynamic phases.

to the load torque but the latter was a direct consequence of the grip force level. Indeed, the angular orientation of the object stabilized when the load torque dropped below the maximal load torque sustainable with the current grip force. Moreover, the subject was able to see the orientation of the object and then had precise visual cues about the position of the center of mass. In the experiment of **Wing and Lederman** (1998) (see Section 1.5 for more details), the subject might have regulated the grip force directly with the position of the off-centered mass, which was visible. So, the grip force baseline was scaled with the load torque but nothing proved that the tactile and/or proprioceptive information was actually used to this end. Note that this hypothesis could have been confirmed if the subjects have been blindfolded. In Chapter 2, the subjects had to manipulate an object in two different configurations producing different load torques. The significant difference of grip force between both load torque levels might only come from a difference of the total mass of the object. In these three experiments, the baseline grip force was scaled with the load torque. However, it was not demonstrated that this correlation was based on tactile or proprioceptive afferents, contrary to the dynamic case, for which the torque variation is well integrated by the sensorimotor system.

The grip force modulation during movements is driven by the global inertial load, combining the forces and the torques (see Chapter 3 and **Goodwin et al.** (1998) description in the Section 1.5). On the other hand, it has been suggested that the control of this grip force modulation and the control of the grip force baseline are two distinct processes (**Crevecœur et al.**, 2009; **Augurelle et al.**, 2003a). This hypothesis was supported by our results with the use of an equivalent mass². During static phases, we observed a remarkably lower level of grip force baseline³ (see Chapter 2) without torque than with torque. In contrast, the grip force modulations around the baseline were similar in magnitude during dynamic phases when a load torque was present or not. This confirms that the control of the grip force baseline does not seem

²The equivalent mass required the same minimal grip force to hold the object without slipping than the manipulandum in presence of load torque. See Chapter 2 and Appendix B for more details.

³termed *static Grip Force* in Chapter 2

to integrate the load torque the same way the control the grip force modulation does.

The slow grip force adaptation in presence of load torque probably comes from a poor ability to use the feedback information. Indeed, until now, nothing formally demonstrates that the scaling of the grip force baseline with the load torque is based on tactile and/or proprioceptive afferents. Visual feedback integration is the only proven way for regulating the grip force baseline. However, it has been shown that grip force adaptation is not based on visual cues (**Flanagan and Beltzner, 2000**). So, a poor tactile and/or proprioceptive perception of load torque could explain inefficient control of grip force baseline and its slow adaptation.

5.3 Limitations and Perspectives

Grip force decrease has been observed across repetitive task (see Chapter 2 and **Crevecoeur et al. (2009)**). But, little is known about the real causes of this grip force decrease. It could be actually due to a real improvement of the internal representation extracting each time more information about object properties. But other explanations, such as an effect of muscular fatigue, are also possible. A better understanding of the origin of the grip force adaptation would certainly help to understand why the load torque has an influence on it. A lead to further investigate the grip force adaptation could be a repetitive grip-lift tasks with imperceptible increases of load between the trials compared to a classical grip-lift task with constant load. A similar grip force adaptation rate in the increasing load condition and in the constant load situation would suggest that the grip force adaption is due to an uncontrolled parameter as muscular fatigue. On the contrary, a slower grip force decrease in the increasing load condition would suggest that the grip force adaptation is actually due to an improvement of the internal models.

The discussion of the previous section (5.2) considers the hypothesis that the grip force baseline cannot be scaled with load torques using only the tactile and/or proprioceptive afferents. However, we have not demonstrated this hypothesis. A potential experiment to test it could be a grip-lift task of different objects with the same mass but different

load torques. The tactile and/or proprioceptive inputs would be proven to be unused, if no correlation is found between the load torques and the grip forces used to stabilize the object.

At the end of the previous section (5.2), we propose the hypothesis stating that our poor tactile and/or proprioceptive perception of load torque during active manipulation is the origin of the slow grip force adaptation. We could confirm this hypothesis assessing the grip force adaptation with a load torque perception proven to be precise. We have shown in Chapter 4 that the CNS is actually able to process the load torque information from tactile afferents during during passive stimulation. An external load torque stimulation with active control of the grip force would be a good method for testing the hypothesis ; for instance, a modified version of the experiment described in **Kinoshita et al.** (1997) or a modified version of Experiment 3 of the Chapter 4. The blindfolded subject would be instructed to adjust his/her grip force to avoid rotation of an unbalanced object. In this situation and according to the results described in Chapter 4, the subject should have a good load torque perception. If the grip force exhibits a fast decrease across the repetitions, it would consolidate the hypothesis that the poor load torque perception is the cause of the slow grip force adaptation.

5.4 Concluding Word

The aim of fundamental research is to develop and improve scientific theories about natural or artificial phenomena. A particularly interesting area is the comprehension of the human body. Understanding the way it works is crucial for example for the great bulk of clinical and robotic applications. Motor control is the interaction between the brain, the muscles, the limbs, the senses, and the environment which allow us to perform a motor skill. In object manipulation, the implicated limbs are essentially the arms and the hands ; the environment includes, for instance, the gravity but essentially the object properties. The presence of load torque is a very important aspect in object manipulation. This is where this work takes place. We showed load torques have major impacts on grip control and we brought new elements to better understand

these impacts.

Appendix A

Vertical movement in presence of an off-centered mass : The mechanical basis

This section describes the basis of the mechanics of a vertical movement in presence of an off-centered mass (M_2 on the Fig. A.1) using the principle of the virtual power.

Let consider the object and the masses as a unique body with the center of mass G placed a distance d of M_1 :

$$d = \frac{M_2}{M_1 + M_2} L \quad (\text{A.1})$$

The position of the center of mass is then:

$$\vec{R} = x\hat{I}_3 + d\hat{x}_1 \quad (\text{A.2})$$

From the position, we can derivate the velocity and the acceleration. As the x base is mobile, the derivative of a vector of this base is $\dot{\theta}\hat{x}_2 \times \hat{x}$.

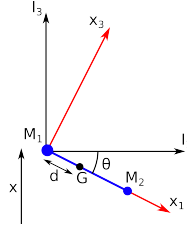


Figure A.1: Schematic representation of the system. The object is represented by the blue line. M_1 is the mass of the object without the off-centered mass and M_2 is the off-centered mass. G is the center of gravity. The fixed axis system is represented in black and the axis system linked to the object in red. In this representation, the object is tilted by a angle θ and lifted up of x .

Then, the velocity is equal to:

$$\begin{aligned}\dot{\vec{R}} &= \dot{x}\hat{I}_3 + \dot{\theta}\hat{x}_2 \times d\hat{x}_1 \\ &= \dot{x}\hat{I}_3 - d\dot{\theta}\hat{x}_3\end{aligned}\tag{A.3}$$

and the acceleration:

$$\begin{aligned}\ddot{\vec{R}} &= \ddot{x}\hat{I}_3 - d\ddot{\theta}\hat{x}_3 + \dot{\theta}\hat{x}_2 \times (-d\dot{\theta}\hat{x}_3) \\ &= \ddot{x}\hat{I}_3 - d\ddot{\theta}\hat{x}_3 - d\dot{\theta}^2\hat{x}_1\end{aligned}\tag{A.4}$$

After that, we compute the angular momentum and its derivative:

$$\vec{H}^G = I\dot{\theta}\hat{x}_2\tag{A.5}$$

$$\dot{\vec{H}}^G = I\ddot{\theta}\hat{x}_2\tag{A.6}$$

with $I = M_1d^2 + M_2(L-d)^2$.

Let define a virtual variation in order to apply the principle of virtual power:

$$\begin{cases} \Delta\dot{\vec{R}} &= \Delta\dot{x}\hat{I}_3 - d\Delta\dot{\theta}\hat{x}_3 \\ \Delta\dot{\vec{\omega}} &= \Delta\dot{\theta}\hat{x}_2 \end{cases}\tag{A.7}$$

Using Equations A.4, A.6 and A.7 we obtain:

$$\begin{cases} M\ddot{R}\Delta\dot{R} &= (M_1 + M_2)[\ddot{x}\hat{I}_3 - d\ddot{\theta}\hat{x}_3 - d\dot{\theta}^2\hat{x}_1][\Delta\dot{x}\hat{I}_3 - d\Delta\dot{\theta}\hat{x}_3] \\ \dot{H}^G\Delta\vec{\omega} &= [I\ddot{\theta}\hat{x}_2][\Delta\dot{\theta}\hat{x}_2] \end{cases} \quad (\text{A.8})$$

$$\begin{cases} M\ddot{R}\Delta\dot{R} &= M[\Delta\dot{x}(\ddot{x} - d\ddot{\theta}\cos\theta + d\dot{\theta}^2\sin\theta) + \Delta\dot{\theta}(d^2 - \ddot{x}d\cos\theta)] \\ \dot{H}^G\Delta\vec{\omega} &= I\ddot{\theta}\Delta\dot{\theta} \end{cases} \quad (\text{A.9})$$

For a simple vertical movement the only resultant force is vertical and the only torque is around $\hat{I}_2$ due to M_2 :

$$\begin{cases} \vec{F}\Delta\dot{R} &= [F\hat{I}_3][\Delta\dot{x}\hat{I}_3] \\ \vec{C}\Delta\vec{\omega} &= [C\hat{I}_2][\Delta\dot{\theta}\hat{x}_2] \end{cases} \quad (\text{A.10})$$

$$\begin{cases} \vec{F}\Delta\dot{R} &= F\Delta\dot{x} \\ \vec{C}\Delta\vec{\omega} &= C\Delta\dot{\theta} \end{cases} \quad (\text{A.11})$$

Using the following principle of virtual power:

$$M\ddot{R}\Delta\dot{R} + \dot{H}^G\Delta\vec{\omega} = \vec{F}\Delta\dot{R} + \vec{C}\Delta\vec{\omega} \quad (\text{A.12})$$

we can equalize the coefficient of $\Delta\dot{x}$ and $\Delta\dot{\theta}$:

$$\begin{cases} M(\ddot{x} - d\ddot{\theta}\cos\theta + d\dot{\theta}^2\sin\theta) &= F \\ M(d^2\ddot{\theta} - \ddot{x}d\cos\theta) + I\ddot{\theta} &= C \end{cases} \quad (\text{A.13})$$

Finally, if the tilted angle is maintained constant, we get:

$$\begin{cases} F &= M\ddot{x} \\ C &= -M_2\ddot{x}L\cos\theta \end{cases} \quad (\text{A.14})$$

This last equations formalize the both mechanical contributions present at the fingers/object interface, the linear force and the torque.

Appendix B

Matching the Global Constraints to Estimate Equivalent Mass to a Load Torque

The local force on the surface of an object subject to mechanical constraint is equal to the force density tensor multiplied by the vector normal to the contact surface. In order to model the contact surface between the object and the fingers, we consider a disc in the plane generated by the X and Y dimensions (Fig. B.1, left). Under this assumption, the force density constraint and normal vector are functions of x and y only. Let $\underline{\underline{\sigma}}(x, y)$ be the 3×3 matrix representing the force density constraint.

The vector normal to the surface is $\underline{\tau}(x, y) = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T$. If the centre of mass is on the grip axis, then the force will have components only in the Y dimensions. Thus, the only parameter of $\underline{\underline{\sigma}}(x, y)$ to be determined is the ratio between the force along the Y axis and the Z coordinate of the normal vector. We call σ_{yz} this parameter (Fig. B.1, left). Now we must take into account that the integration of the local forces on one contact surface must be equal to half of the weight of the object, assuming that the object is static and that the weight is equally distributed across the two fingers. For a mass M and a contact area A , we must

solve the following equation:

$$\int_A \sigma_{yz} dA = \frac{-Mg}{2} \quad (\text{B.1})$$

with g representing the gravity. It gives directly:

$$\sigma_{yz} = \frac{-Mg}{2A} \quad (\text{B.2})$$

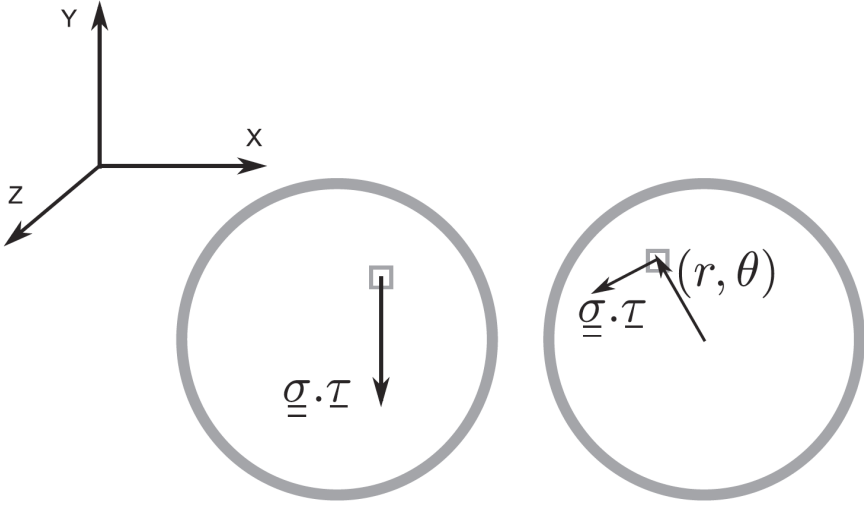


Figure B.1: Representation of the local forces on the contact surface between the manipulandum and the fingertips. The left plot shows that, when there is no torque, the local force is parallel to the direction of the weight (vertical). The integral of this local force on the two sensors must be equal to the weight. The right plot shows that in the presence of a torque only, the local constraint on the point (r, θ) is orthogonal to the vector joining (r, θ) with the centre of the contact surface, and proportional to r by a factor α . This local constraint produces a moment relative to the centre of the contact surface. The integral of local moments across the contact surface on the two sensors must be equal to the torque induced by the off-centered mass.

Let us now assume that a tangential torque equal to T is applied to the contact surface. We further assume that the local force at (x, y) is orthogonal to the vector (x, y) and proportional to the distance from the center of the disc by a factor α (Fig. B.1, right). Again, we must

integrate the moment of the local forces relative to the center of the disc and make it equal to half the torque. The integral is computed in polar coordinates as follows:

$$\int \int_A \alpha r^3 dr d\theta = \frac{T}{2} \quad (\text{B.3})$$

which gives

$$\alpha = \frac{T}{AR^2} \quad (\text{B.4})$$

We now use a simple argument of linear addition in order to estimate the force density tensor taking into account the total mass and torque by using Eqns. B.2 and B.4 expressed in Cartesian coordinates. We find:

$$\underline{\underline{\sigma}}(x, y) = \begin{bmatrix} 0 & 0 & -\frac{T}{AR^2}y \\ 0 & 0 & \frac{T}{AR^2}x - \frac{Mg}{2A} \\ -\frac{T}{AR^2}y & \frac{T}{AR^2}x - \frac{Mg}{2A} & 0 \end{bmatrix} \quad (\text{B.5})$$

The equivalent mass is defined as follows: we need to find a mass, say M_E , such that the integrated square of the norm of the force density constraint for this mass, without torque, gives the same number as the same quantity computed with the tensor given in Eqn. B.5. The integrated square of the norm of the force density constraint in the presence of a torque (Eqn. B.5) gives:

$$\int_A \| \underline{\underline{\sigma}}(x, y) \underline{\underline{\tau}}(x, y) \|^2 = \frac{2\pi T^2}{4A^2} + \frac{M^2 g^2}{4A} \quad (\text{B.6})$$

We now have to solve:

$$\frac{2\pi T^2}{4A^2} + \frac{M^2 g^2}{4A} = \frac{M_E^2 g^2}{4A} \quad (\text{B.7})$$

which gives:

$$M_E = \sqrt{\frac{2\pi T^2}{Ag^2} + M^2} \quad (\text{B.8})$$

This expression was used with the parameters given in the Methods of Chapter 2 (see Section 2.2) in order to estimate the equivalent mass used in Experiment 3 of Chapter 2.

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