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## Tactile interfaces and postural control

Angéline Bellicha

► **To cite this version:**

Angéline Bellicha. Tactile interfaces and postural control. Biomechanics [physics.med-ph]. Sorbonne Université, 2021. English. NNT : 2021SORUS071 . tel-04091732

**HAL Id: tel-04091732**

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Submitted on 9 May 2023

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THÈSE

présentée pour obtenir

le titre de docteur délivré par Sorbonne Université

École doctorale: Sciences Mécaniques, Acoustique, Électronique et Robotique de Paris

*par*

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## Interfaces Tactiles et Equilibre Postural

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# Résumé

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L'intégration sensorielle est nécessaire au contrôle de la posture. En position debout, le corps oscille, il dérive au sein des limites de stabilité. Dans cette thèse, nous étudions la Prise Légère qui peut être définie comme tenir légèrement un bâton ou une canne qui touche le sol sans stabiliser le corps mécaniquement. Le balancement est réduit lors d'une Prise Légère. Elle fournirait un point d'ancrage dans l'espace, une référence externe fixe et des informations transitoires sur les oscillations du corps. Des études montrent que le contrôle postural peut être modifié par l'ajout d'une tâche supra-posturale ou par la volonté; le balancement peut être réduit volontairement. Nous questionnons si le balancement peut être volontairement réduit grâce aux informations fournies par la Prise Légère. Des informations sensorielles supplémentaires peuvent être fournies par des dispositifs de biofeedback; leur utilisation permet une réduction du balancement. Nous questionnons si ces informations peuvent être utilisées conjointement avec les informations de la Prise Légère pour minimiser volontairement le balancement. Nous montrons que les informations de la Prise Légère peuvent être utilisées pour réduire volontairement le balancement et qu'un biofeedback peut être utilisé pour le réduire davantage en présence d'une Prise Légère. Nous utilisons une analyse dans le domaine fréquentiel étant donné la nature des informations de la Prise légère et du balancement. Nos résultats critiquent la minimisation du balancement autour d'une référence unique comme non écologique et remettent en question la minimisation du balancement comme objectif du contrôle postural.

**Mots Clés** : Contrôle Postural, Prise Légère, Biofeedback Tactile, Minimisation Volontaire, Intégration Sensorielle, Analyse Fréquentielle



# Abstract

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Sensory integration is necessary for the control of posture. When upright, the body sways even in quiet stance. The body drifts within the stability boundaries. When an individual lightly grips a stick or a cane, sway is reduced. In this study we focus on Light Grip. Light Grip can be defined as lightly holding a stick or a cane touching the ground without providing mechanical support. It is generally assumed that Light Grip is like an anchor in space, providing an external stationary reference and transient cues of sway. This can be seen as providing information about the position of the contact and the velocity of the body. Different studies show that postural control is cognitively penetrable. It can be altered by the addition of a supra-postural task or by volition. Studies have shown that sway can be voluntarily minimized. We question whether Light Grip cues can be used to voluntarily minimize sway. Supplemental sensory information can be provided by Biofeedback devices. Studies have shown that sway can be reduced using biofeedback devices. We question whether the supplemental information can be used, voluntarily, conjointly with Light Grip cues to minimize sway. In this thesis, we show that Light Grip cues can be used to minimize sway voluntarily. We show that a biofeedback can be used to further minimize sway in presence of Light Grip cues. We use frequency analysis given the oscillatory nature of sway and the nature of Light Grip cues. Our findings support the idea that minimizing sway around a unique reference in space is not ecological and that minimization of sway might not be the goal of postural control.

**Keywords** : Postural Control, Light Grip, Tactile Biofeedback, Voluntary Minimization, Sensory Integration, Frequency Analysis



# Remerciements

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Je souhaite tout d'abord adresser mes plus vifs remerciements à l'ensemble des membres du jury ayant accepté d'évaluer le travail effectué durant cette thèse. Je tiens à remercier en particulier Mr Philippe Fraisse et Mr Hadrien Ceyte d'avoir accepté d'être les rapporteurs. Je tiens à remercier Mme Catherine Achard et Mr Jérôme Szewczyk d'avoir accepté d'être membre de mon jury. Je tiens à remercier Mme Catherine Achard, Mr Emmanuel Guigon, Mme Malika Auvray et Mr Ludovic Saint-Bauzel pour leur écoute et leur aide que ce soit sur le plan scientifique ou relationnel. Je remercie Mr Wael Bachta d'avoir accepté d'être mon directeur de thèse sans qui cette thèse n'aurait pas été possible et qui a cru en moi. Je remercie Mr Andres Trujillo-Leon et Mr Fabien Vérité qui ont encadré mon travail et pour toute leur aide qui m'a été extrêmement précieuse et le temps qu'ils m'ont consacré.

Merci à l'équipe d'ingénieurs qui m'ont aidé à résoudre tous ces problèmes qui me semblaient sortir du néant. Je repense à David et l'aide qu'il m'a apporté lors de mon stage ou avec la plateforme quand j'étais recouverte de marqueurs ou Florian et le temps qu'il a passé dans le hall Sima à m'aider avec les mystères de Simulink ou toutes ces impressions pour fixer un capteur d'effort. Merci à l'équipe administrative qui s'est toujours montrée patiente et compréhensive face à mon manque d'organisation administrative.

Je tiens à remercier l'équipe de l'institut Joseph Stefan en Slovénie et tout particulièrement Daša. Merci beaucoup pour cette expérience ; j'ai été très heureuse de vous rencontrer, de travailler avec vous et du temps passé ensemble bien que bref.

Un énorme merci à tous les membres de l'ISIR et plus particulièrement ceux de l'équipe AGATHE et du club d'Haptique. Sans vous, les choses auraient été très différentes et je pense avec beaucoup de chaleur aux moments passés ensemble qui ont illuminé mes journées. Mon bureau, J08, Mario, Rémi, Mathilde, Omar, Charlotte un peu plus tard et bien sûr Mégane, ce merveilleux bureau. Eléonore, Clémence, Etienne,



Félix, Josh, Jésus, je ne vous cite pas tous mais je vous remercie pour ces bonbons à la réglisse, ces discussions sur le contrôle moteur, ces parties de badminton et toutes ces choses qui nous rendent heureux. Vous me manquez et me manquerez. Je ne sais pas quoi vous dire si ce n'est que vous m'avez permis de m'accrocher et de tenir dans les moments difficiles et d'être heureuse dans les moments plus doux. Je pense avec joie à toutes ces rencontres dans la cuisine, à tous ces doctorants aux sujets variés qu'on ne connaît jamais assez et à ces expériences parfois si surprenantes qui ne peuvent qu'attiser la curiosité. Je ne peux évidemment que vous remercier pour toutes ces expériences que vous avez passées et bien que certaines ne soient pas dans mon manuscrit, je peux vous assurer qu'elles ont nourri ma réflexion et qu'elles n'ont pas été vaines.

Enfin, je remercie du fond du coeur ma famille; Maman, Fanny, Robin, je vous remercie d'avoir été là, pour votre soutien et pour votre gentillesse; Maman, tu m'as aidé jusqu'au bout, je t'en remercie infiniment. Yanis, mon amour, je te remercie pour ta présence, ton calme, ta gentillesse et ton aide indéfectible. Vous avez cru en moi et m'avez soutenu. Cette thèse et l'écriture de ce manuscrit auraient été bien différentes sans vous. Merci.

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# Introduction

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Imagine a hiker standing in the forest, the feet on the uneven ground, a camera in his hands, ready to take a picture. I hardly imagine he is afraid of falling. He is standing upright, probably talking to his friend about a complicated problem he is facing and yet he is still not falling. We continuously adapt our posture to make the tasks we perform easier, our hiker might need to tilt his body to get a better view of a bird up in a tree. There is not only one standing upright posture but an infinite amount of variations. Our hiker might not realize that complex mechanisms are at play behind this apparent simple task. The upright stance is inherently unstable, one can think of it as a breathing inverted pendulum. Simply by standing on the ground, we are interacting with the environment, at least through the feet. The perception of the environment we interact with and how our body is moving in it is crucial for postural control. Numerous sensory information are used to estimate the state of the body in space (position, motion...). These information can be provided by vision, the vestibular system, the proprioceptive system or by the haptic system through proprioception and touch. Another way to provide information about the state of the body is through the use of biofeedback devices. While the body might seem static from afar, it is constantly swaying. The amount and the structure of sway is affected by sensory conditions. For example, sway amplitude and velocity is reduced by opening the eyes or lightly touching a fixed surface. Imagine for a brief moment that our hiker wants to take a picture, the image is blurry so he lightly grips a fragile branch and he tries to minimize the movement of his body. In this thesis, we question the ability to voluntary control sway using sensory information. Light Grip (defined as lightly gripping a stick or a cane that does not provide mechanical support) and Vibrotactile biofeedbacks are used. The task chosen to investigate this voluntary control is a minimization of sway task. This task was chosen as it is commonly used in the literature, this allows comparisons of methodology and results. The capacity to minimize sway is used to assess the control but is not used to assess an increased stability. We expected that sway could be voluntary reduced with Light Grip and with the two biofeedbacks tested.

In the first chapter, the state of the Art of Postural control in general, Light Grip and Biofeedback are first presented. Hypotheses and contributions are also detailed.

In the second chapter, we present the general methods of our study with a brief review of metrics found in the literature and a description of common aspects of the different experimental setups used in this thesis and metrics chosen.

In the third chapter, we study the influence of Light Grip in a relaxed stance in the time and frequency domain. The correlation of Light Grip cues and sway is investigated. This experiment allows us to investigate Light Grip in relaxed quiet stance before studying the effect of the voluntary reduction task.

In the fourth chapter, we study the voluntary use of Light Grip cues in a minimization of sway context. We investigate the effect of Light Grip for a relaxed and still (active minimization) stance. This experiment was conducted with and without Light Grip and with and without Vision. A frequency-domain analysis is used to compare the minimization of sway depending on the sensory context and can be used to question the minimization of sway as the goal of postural control.

In the fifth chapter, we study the use of vibrotactile Biofeedbacks in a minimization of sway task. The biofeedbacks are provided in the hand. We investigate the use of two biofeedbacks in presence or absence of a Grounded Grip (handle rigidly tethered to the ground, this is the Light Grip presented in the other chapters). These biofeedbacks do not provide the same amount of information. This experiment is used to assess the use of a vibrotactile biofeedback with Light Grip and to question whether all variability should be reduced if a part is useful for the voluntary control of sway.

# Chapitre 1

## State of the Art

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## 1 A brief Introduction to Postural Control

### 1.1 Standing and Stability ?

We can define upright stance as a group of postures characterized by the verticalization of the body. Upright Stance facilitates numerous tasks such as grabbing objects in high spots or looking far ahead. It is crucial to stay autonomous. The body is highly unstable in upright stance. Postural control is needed to maintain balance in order to remain upright (Wade & Jones, 1997). However, postural control is not just about maintaining the equilibrium of a highly unstable system or standing still, controlling posture is about maintaining balance while orientating the body in space to perform tasks in complex and changing environments that potentially destabilize us (Horak, 2006 ; Massion, 1992). Postural control seems simple and automatic from afar. However, a closer look at the postural system reveals its complexity. We are standing in an environment that acts on us and that we act on simply by standing on our feet. We must be able to perceive the environment and ourselves in it. Postural control can be described as a perception-action loop. Postural control can be summarized as the generation of adapted/appropriate actions to answer the demands of a task, postural and/or supra-postural given sensory information. The postural system consists in several interacting subsystems : A musculoskeletal subsystem, necessary for the production of movements. A sensory subsystem, used to apprehend the environment and the state of the body in the environment. A neural subsystem with the Central Nervous System (CNS) to orchestrate, in part at least, the actions of the different subsystems.

### 1.2 The musculoskeletal System

The musculoskeletal system or the biomechanical plant can be seen as a kinematic chain formed of multiple non-rigid bodies connected by joints. Muscles, tendon and other structures of the body are used to generate the movement of the different bodies relative to one another or relative to the ground. The movements of the limbs do not only depend on the motor commands but also of their mechanical characteristics. The number of joints and muscles across the body afford many degrees of freedom, the body is thus redundant. This redundancy implies that there are many ways to stand upright (Ting, 2007). The many degrees of freedom provide a great flexibility, the body is allowed a

great amount of possible postures allowing us to perform activities such as reaching for an object, shooting an arrow or just quietly standing. The feet might be resting at a specific position in space, the body, as a whole, is not fixed in a precise posture (Marin & Bardy, 2011).

### 1.3 Sensory Systems

Self-motion perception in space is the result of the combination and integration of difference sensory inputs. This kinesthetic percept is built by the CNS based on visual, vestibular, proprioceptive cues and/or haptic cues combining proprioceptive and tactile cues.

The sensory information are attached to specific reference frames, are noisy and possibly in conflict. Furthermore, the sensory estimate of the state of the system reflects a past state of the system and not the current state. There are delays in the sensory feedbacks.

Vision provides information about the position and the motion of the head relative to the surrounding visual space. The vestibular system is responsible for the perception of the movement and orientation of the head compared to the gravity vertical like an accelerometer and a gyroscope. The haptic system regroups proprioception and touch. While proprioception provides information about the velocity, position and orientation of the limbs and the force applied and received, touch or tact provides information about the contact, the pressure applied, the slip, the stretch, the vibrations and even temperature. We can easily think of proprioception for the legs and the touch by the feet for quiet stance but there are other sources of haptic cues. Light Touch or Light Grip (contact of the finger or the hand) is considered to provide sway-related haptic cues. Proprioception cues do not only participate to the haptic system. Sensory information about self-motion can also be provided by external devices, biofeedback devices.

### 1.4 The Central Nervous System

The Central Nervous System (CNS) is usually presented as having different levels, organized hierarchically in terms of complexity or transmission delays.

Scott (2004) explains that the spinal cord is responsible for the rapid reflex movements that do not require supra-spinal participation but also the transmission of motor commands and sensory feedback from and to supra-spinal levels.

There are supra-spinal regions, including brainstem regions, cerebellum and the cortex. Some parts are responsible for rhythmic or automatic movements while others are responsible for a great variety of motor behaviours, including voluntary movements.

## 2 Sensorimotor Control

Observations of individual standing show that the body is perpetually moving, the body sways even during quiet stance. Sway reflects the combined action of the neural system that controls movements and the mechanical properties of the different limbs in play (Scott, 2004) for motor control in general).

### 2.1 The Center of Pressure and the Center of Mass

In quiet, bipedal, feet apart, stance, body motion is foremost present in the Antero-Posterior (AP) direction (or in the sagittal plane) around the ankles. The body has thus been modelled by many researchers as an inverted pendulum.

#### 2.1.1 The Center of Mass : The Controlled Variable

In posturography, the name Center of Mass (COM) is used for the weighed average of the COM of each body segment in 3D space (Winter, 1995). Using the Inverted Pendulum model, the COM can be used to describe the movement of the body in space, usually referred as **sway** (Baratto, Morasso, Re, & Spada, 2002). The Center of Mass is referred as the **controlled variable** of postural control (Morasso, Baratto, Capra, & Spada, 1999). The projection of the Center of Mass must remain inside the **Support Polygon/surface** to maintain balance. The support polygon or support surface is defined by the area under and between the feet. The support polygon is the convex hull of the feet sole on the ground. It is represented in Figure 1. We would like to note that keeping the Center of Mass above the Support Polygon does not necessarily imply reducing its displacements inside the polygon.

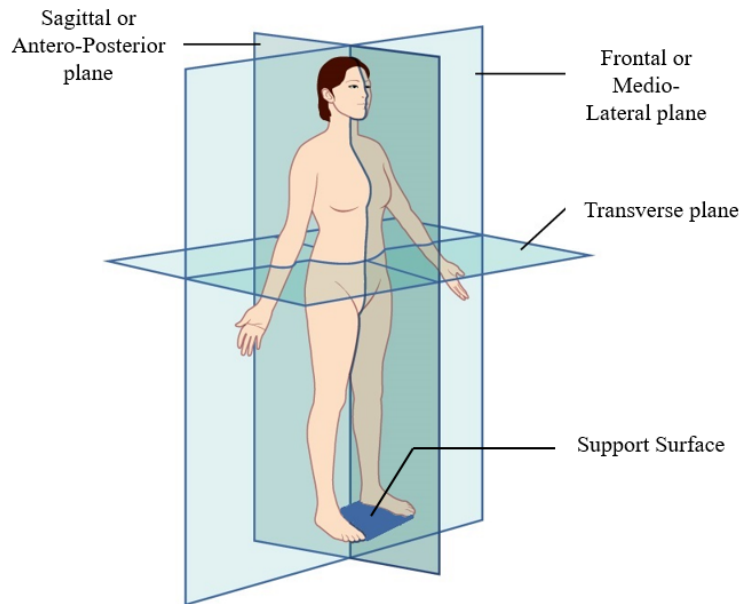


FIGURE 1: Anatomical Planes and Support Polygon. Modified image from *cnx.org*

### 2.1.2 The Center of Pressure : The Controlling Variable

The body on contact with the ground via the feet soles is applying forces on the ground as it sways. The Center of Pressure (COP) represents a weighted average of all the pressures over the surface of the area in contact with the ground. [Sardain et Bessonnet \(2004\)](#) explain that the field of pressures forces normal to the sole can be modelled by a resultant force. This force is applied at a point where the resultant moment is zero. This point of application is called COP. With an inverted pendulum model, the COP signal is thus a **scaled version of the ankle torque**, its trajectory represents the time-varying forces generated by the muscles in the stabilization of the body ([Baratto et al., 2002](#)). The COP is considered to be the **controlling variable** of postural control.



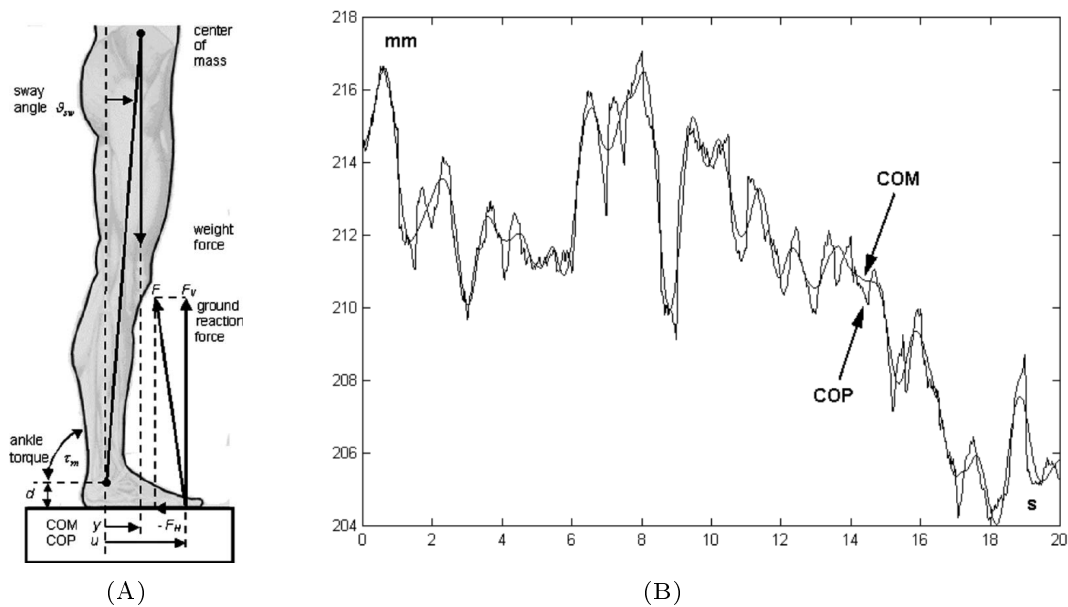


FIGURE 2: (A) Representations of the COP and COM (B) COP and COM time series from the study by Baratto et al. (2002)

### 2.1.3 The Link between the Center of Pressure and the Center of Mass

The Center of Mass is referred as the controlled variable while the Center of Pressure is referred as the controlling variable.

It is necessary to keep in mind as explained by Baratto et al. (2002) that the Center of Mass (COM) signal represents the sway of the body modeled as an inverted pendulum while the Center of Pressure (COP) signal does not represent a movement but a point of application of a force. Both COP and COM are represented in Figure 2A. We can clearly see that they do not coincide.

The representations of the COM and COP through time showed in Figure 2B illustrates that the COP is moving rapidly around the COM. The two signals are in phase but the COP has a richer frequency content than the COM. Studies showed that the two signals are very similar for frequencies below  $0.5Hz$  (Benda, Riley, & Krebs, 1994). The similarity and the synchrony of the two signals is not the reflect of a control mechanisms but is of mechanical origin (Baratto et al., 2002); the body is acting like a low-pass filter.

As it can be seen on the Figure 2B, the COP and COM signals are highly variable in time even for quiet standing. COM or COP time-series are bounded **non-stationary** within the bounds of the support surface (Carroll & Freedman, 1993; M. Riley, Stof-fregen, Grocki, & Turvey, 1999). The variability across frequencies is not constant with a greater variability for low frequencies as noted by Bense et Dzenolet (1968) or Zatsiorsky et Duarte (2000). While the COM and COP provide valuable information on

sway and postural mechanisms, the number of postures that can be adopted to stand upright question whether sway of the COP or COM are sufficient to describe whole body movements.

## 2.2 Postural Control

Postural control is necessary to **maintain balance** and to **orientate the body** in space (Horak, 2006). These two functions are not independent but intertwined in on complex system. Postural control is an example of **sensorimotor control** that can be seen as a perception-action cycle/loop. Ernst et Bühlhoff (2004) represents this cycle, proposed by Bernstein. The cycle presented by Ernst et Bühlhoff (2004) is in Figure 3.

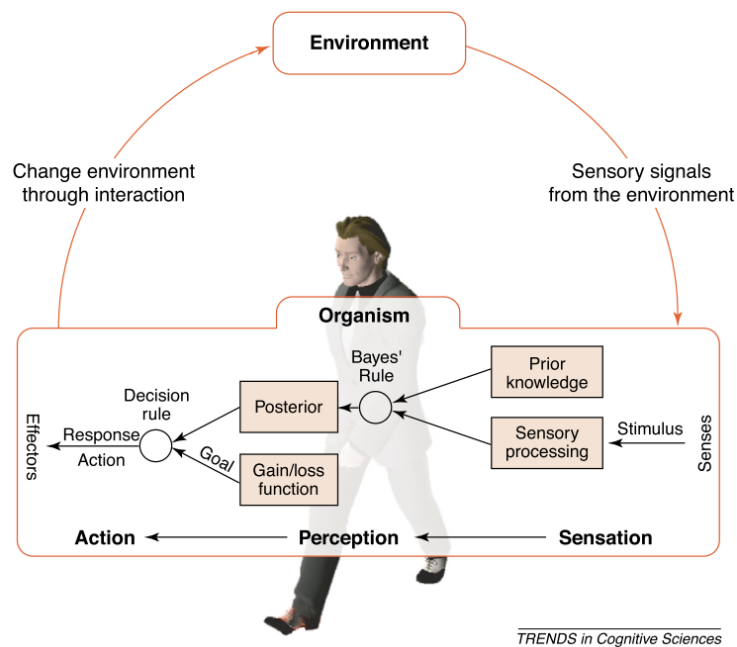


FIGURE 3: Perception-Action loop from (Ernst & Bühlhoff, 2004)

Sensory information about the body state (position, motion) in the environment needs to be integrated in order to find the appropriate action to fulfil the requirements of the postural task.

### 2.2.1 Postural Control Mechanisms

Due to the upright configuration of the body (reducing the support polygon and elevating the position of the Center of Mass), to the internal (respiratory function) and external forces applied (gravity) and the tasks constraints (grasping objects or moving

the arms), the system/body is highly unstable. To maintain balance, the COM must remain above the support surface.

Researchers, [Winter, Patla, Prince, Ishac, et Gielo-perczak \(1998\)](#) amongst others, summarized postural control as a spring-damper controller. The muscles and tendons in the back of the leg would act like springs and dampers to bring back the COM to a reference position. The CNS participation was reduced to the setting of the gains or had none at all. However, the **mechanical properties of the tendon-muscles cannot** account for a quarter of the stiffness required to **stabilize stance** according to [Morasso et Schieppati \(1999\)](#). Furthermore, [Loram, Maganaris, et Lakie \(2004\)](#) showed that the muscles shortening and lengthening during stance were not consistent with a spring-damper controller.

While the mechanical properties (visco-elastic) of the legs play a role in postural control, other mechanisms exist and are necessary. The generation of the adapted motor commands relies on the integration of sensory information used to compensate and anticipate the movements of the body.

Posture is controlled in a **closed-loop scheme**. The task or set-point of postural control can be referred as the desired state of the system. The desired state is fed to the controller that compares the desired state to the estimated state. The estimation of the state of the system (position, velocity of the body) is possible thanks to the **integration of sensory information**. The delays in the sensory feedback are however important and can thus threaten stability (100 to 300ms) ([Morasso, Baratto, et al., 1999](#)). It is assumed that a copy of the motor commands are fed to the state estimator that is used to predict the outcome of the motor commands on the state of the system using internal models.

Figure 4 is a modified version of the feedback loop presented by [Scott \(2004\)](#). The different loops are represented.

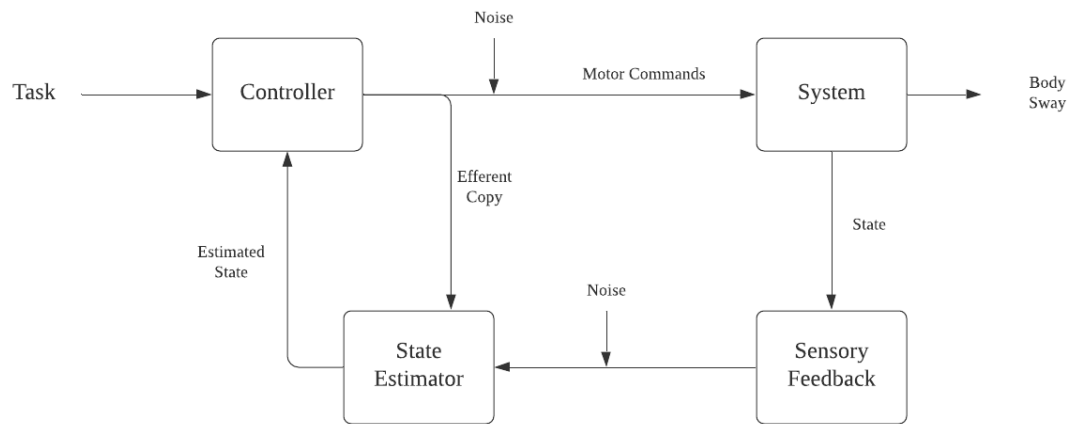


FIGURE 4: Feedback Loop

The traditional theory (supported by [Winter et al. \(1998\)](#) amongst others), or sensory approach, provides an explanation for the decreased or increased variability of COP or COM oscillations with the addition or removal of sensory information. This theory associates a decreased variability with an increased stability. The goal of postural control would be to minimize body sway. The oscillations of the body are explained by sensory and motor noise. Providing sensory information would allow a reduction of noise and thus a reduction of sway. This theory supposes that **standing is equivalent to minimizing sway**.

However, it has been shown that the amount of sway can be modified by volition, in other words, **sway can be voluntarily reduced** ([R. C. Fitzpatrick, Taylor, & McCloskey, 1992](#) ; [Loram, Kelly, & Lakie, 2001](#) ; [Reynolds, 2010](#) ; [Zok, Mazzà, & Cappozzo, 2008](#)). While the reduction is possible in absence and presence of visual cues, sway can be greatly reduced with visual information ([R. C. Fitzpatrick et al., 1992](#) ; [Loram et al., 2001](#) ; [Reynolds, 2010](#)). It has also been shown ([Reynolds, 2010](#)) that the amount of sway that can be reduced reflects the difficulty of the standing task (feet together, tandem-romberg, feet apart). [Loram et al. \(2001\)](#) explain the reduction is not the result of an increased impedance (stiffness and viscosity of the ankle joint) but is possible thanks to an active and predictive dampening of the ankle motor torque noise. [Sciada, Dalton, et Nantel \(2016\)](#) question the influence of the stiffening of the body on postural sway. They compared the sway of participants actively reducing sway or actively reducing sway by stiffening the body. They found that sway amplitude and velocity were increased with the stiffening strategy compared to the other strategy.

This voluntary minimization of sway is the task used in this thesis to study the **voluntary control of sway**. The voluntary control of sway has also been studied by voluntary changes of posture on a moving or still support surface. For instance, [Buchanan](#)

et Horak (2003) explain that the voluntary transition between two postures **requires the CNS to pre-plan** the transition based on sensory and mechanical constraints.

Gatev, Thomas, Kepple, et Hallett (1999) explain postural control by saying that it is the **predictive modulation of muscular activity**. The predictive modulation is revealed by the positive correlation of the gastrocnemii activity (EMG) and COP or COG (Center of Gravity) with the muscular activity leading sway. They explain that this feedforward control of muscular activity is only possible because of the low frequency content of sway that allows the modulation of the gastrocnemii activity. Furthermore, they explain that this feedforward control is necessary to deal with the feedback delays, this is in line the explanation in (Morasso, Baratto, et al., 1999). They explain that the correlation of the EMG and sway shows that sway is allowed by the controller. Moreover, they explain that little predicted movements can be used to explore the stability limits.

van Emmerik et van Wegen (2002) explain that **variability** may be the sign of a **stable, healthy and flexible system**. Theories like the Uncontrolled Manifold or the *minimal intervention principle* propose that variability is only reduced if it hinders the result of the action and not if it does not (Todorov, 2004).

Duarte, Zatsiorsky and colleagues explain that in upright stance, **the body drifts**. This drift would induce a modulation of the muscular activity. These drifts would be allowed as long as stability is not threatened. They explain that these unintentional drifts are most **likely fundamental to the performance of tasks in daily life** and that they should not be seen as a threatened stability (Rasouli et al., 2017). They also explain that these drifts are very variable between participants. This drift can be identified on the COP or COM spectrum for frequencies below  $0.1Hz$  (Yamagata, Popow, & Latash, 2016).

In line with Gatev et al. (1999), the exploratory theory proposes a functional role of variability. The **movement of the body is used to gather sensory information**. This exploration would allow the system to test its limits of stability. Carpenter, Murnaghan, et Inglis (2010) amongst others (Wade & Jones, 1997) study this theory explaining the oscillations of the body are not the result of noise or error but a strategy to maintain balance. Individuals usually performs other tasks while standing, we rarely only stand. We think of the acquisition of upright stance to reach objects in high spots or to look far ahead. These tasks we perform while standing are called **supra-postural tasks**, they can be motor such as reaching for an object or cognitive such as reading a sign. The addition of supra-postural tasks while standing, may they be motor or cognitive is known to modify body sway (Mitra & Fraizer, 2004; Shumway-Cook & Woollacott, 2000). The modification of body sway variability may it be in terms of amplitude, velocity or frequency content during concurrent tasks supposes that **postural control**

shares attentional resources with other cognitive processes (Pellecchia, 2003 ; M. A. Riley, Baker, Schmit, & Weaver, 2005). However, the effect of a concurrent task is very different from one study to the other. Fraizer et Mitra (2008) provide a review of the proposed explanations of these differences. These differences highlight the complexity of postural control. Indeed, **not all tasks are equivalent**. Some can be facilitated by postures while other cannot ; some hinder the control of posture while others do not ; some use sensory resources while others do not (Ceyte et al., 2014 ; M. A. Riley, Mitra, Saunders, Kiefer, & Wallot, 2012 ; T. A. Stoffregen, Hove, Bardy, Riley, & Bonnet, 2007). Furthermore, when a supra-postural task is added, it can be prioritized or not depending the precision demands of the supra-postural task and whether balance is challenged (Mitra & Fraizer, 2004). The prioritization also depends of the instruction given to the participant.

The **facilitation theory** explains that postural control enables and facilitates supra-postural tasks (if these tasks can be facilitated by posture). This theory is supported amongst others by T. Stoffregen et Pagulayan (2000) or M. Riley et al. (1999). T. Stoffregen et Pagulayan (2000) compared the body sway for a visual search task and found that sway was greatly reduced with the most difficult task. This highlights that sway can be modulated to facilitate a supra-postural visual task.

Wulf, McNevin, et Shea (2001) ; Wulf et Prinz (2001) and many others (Vuillerme & Nafati, 2007) explain using the *constrained action hypothesis* that **focusing the attention to how a movement is performed can hinder the performance of the movement**. This is called an **internal focus**. Vuillerme et Nafati (2007) explain that an internal focus during upright still stance can induce an increased neuromuscular activity. A voluntary control of sway likely induces an internal focus of attention. **Focusing the attention on the effect of the movement can promote a more efficient and automatic control**. This is an **external focus**. For example, the task to minimize the movement of a curtain touched with a finger induces an external focus while the task to minimize the movement of the body without another task induces an internal focus. The addition of supra-postural task can shift the attention focus toward an external focus.

### 2.2.2 Perception

**Perception** An accurate, non-ambiguous and robust perception of the movement and position of the body in space is crucial for postural control. This kinesthetic perception is the result of the **combination and integration of difference sensory inputs**. The different sensory inputs, Vision, the Vestibular system, Proprioception, the Haptic

system (Proprioception and touch) are attached to specific reference frames, noisy and possibly in conflict.

Ernst et Bühlhoff (2004) explains that in order to come up with a robust and non-ambiguous perception, the CNS combines a maximum of sensory signals that are integrated to reduce the variability of the estimation. Prior knowledge can be used to resolve ambiguities. However, in specific situations, kinesthetic illusions can be evoked.

Resolution of ambiguities can be described by an example. Imagine lying down, eyes closed, on a floating pontoon. Proprioception and touch are telling you that you are lying down and not moving. Your vestibular system is telling you that you are moving. Several options are possible to disambiguate this situation. Opening your eyes and looking at the bank will tell you that you are indeed moving. This is sensory cooperation. If you cannot open your eyes for whatever reasons, there is prior knowledge, you know that you are on a floating pontoon and you know that you are neither sick nor drunk. This is disambiguation using priors.

Integration is not a simple addition of sensory signals or the choice of one sensory signal over the others. Every signal is noisy but the variability of each sensory information is not the same. This difference in variability of the different signals can be used to reduce the variability of the estimate.

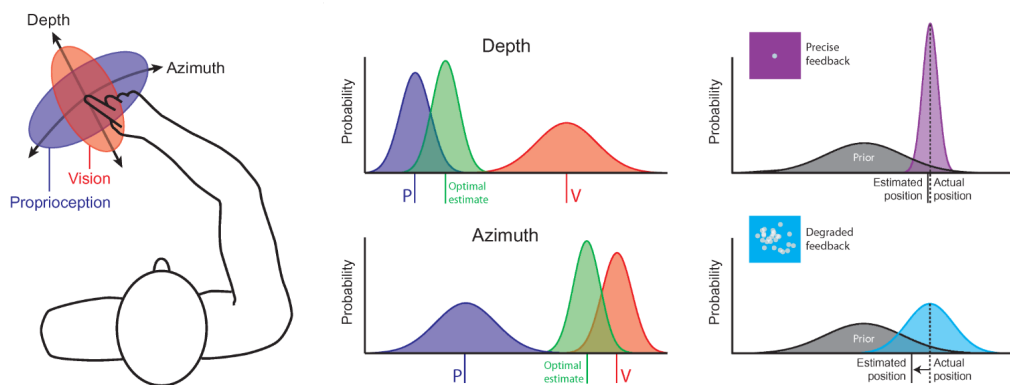


FIGURE 5: Sensory reweighing From (Bays & Wolpert, 2007)

The integration of two different sensory inputs is presented in Figure 5 from (Bays & Wolpert, 2007). In this example vision and proprioception provide information regarding the position of the finger. The estimation provided by each input is more variable in one direction than the other expressed by a wider blob for higher variability. Proprioception is more accurate for depth perception while Vision is more accurate for azimuth perception. The estimated position is the result of the integration of the two information considering the variability of both sensory inputs in each component (azimuth and depth). The input

that provided the most likely estimation for each direction is given more weight than the one less likely.

The **sensory information are weighted** as a function of how likely it is that they are capturing well the environment. This process presents non-linearities.

We would like to note that the CNS has only access to perception, to an estimation of the environment and not to reality or to the "ground truth".

**Proprioception and Touch** Proprioceptive cues provide information regarding the position, velocity and orientation of the limbs as well as the force exerted by the muscles (Proske & Gandevia, 2012). Different receptors are described to participate to proprioceptive perception : the neuromuscular spindles and the golgi organs. The neuromuscular spindles are along the muscular fibres. They measure the lengthening and shortening of the muscles. Golgi organs located at the junction of tendons and muscular fibres measure the force exerted by the muscles.

The tactile mechanoreceptors are usually divided into different categories (Ackerley & Kavounoudias, 2015) :

- Rapidly or fast adaptive (RA or FA) receptors (Meissner and Paccini receptors) that provide information about vibration and rapid changes. They are most likely providing information about the velocity of the body/movement.
- Slowly adaptive (SA) receptors (Merkel and Ruffini receptors) that provide information about the indentation of the skin or pressure and the stretch of the skin. They are most likely providing information about the position of the contact.

**The haptic system combines proprioception and touch.** When our body interacts with the environment, be it through the feet during quiet standing without any other contact or to manipulate objects or just to lightly touch an external surface, proprioceptive and tactile cues are combined together. They can be used to **estimate how our body is interacting with the environment and how the environment is interacting with us.**

Proprioception and touch are combined to build a kinesthetic percept. Rabin et Gordon (2004, 2006) explain that **tactile information are used to calibrate proprioceptive information as touch provides a external spatial reference.**

Touching is at the same time a perceptual and motor performance (Mauerberg-Decastro et al., 2014). Sensory feedback is necessary to manipulate and manipulating is often necessary to get a sensory feedback. The feedback loop used to explain postural control can also be used to describe the exploratory movements. During the exploration



of a surface, a comparison between the tactile and proprioceptive inputs and the expected inputs is used to modify the behaviour and the representation of the world.

**Proprioceptive and Haptic Cues for Postural Control** Kinesthesia is crucial for postural control as it provides information about the movement of the body but also about the limbs. The importance of kinesthesia can be highlighted by proprioceptive (Goodwin, McCloskey, & Matthews, 1971) perturbations.

Vibrations of the leg muscle bellies and tendons have been used to study proprioceptive-driven kinesthetic illusions. When standing, a vibration of the Achilles tendon ( $90Hz$ ) evokes the perception that the calf muscles are stretched as if the person had leaned forward. In response to the perception of a forward lean, the body leans backwards (Caudron, Boy, Forestier, & Guerraz, 2008 ; J. R. Lackner, Rabin, & Dizio, 2000).

When we stand, our body is in contact with the ground via the feet sole. The limbs are moving and applying pressure and stretching the skin of the feet soles.

Morasso, Baratto, et al. (1999) explain the SA mechanoreceptors are likely providing information about the position of the COP while the RA mechanoreceptors are providing information about the rapid changes around the position, in other words, they provide information about the difference between the COM and the COP.

Foam under the feet can be used hinder the use of the ankle proprioception as well as the use of the feet cutaneous receptors. Isableu et Vuillerme (2006) studied the influence of added foam under the feet compared to a firm floor for 140 participants. They found that participants swayed more and faster with the foam than without it. Surprisingly they found that participants who swayed less without the foam were the one who swayed more with it. These findings highlight the influence of proprioceptive and tactile cues of the feet for postural control but also highlights the different sensory weighting between individual.

R. Fitzpatrick et McCloskey (1994) explain that in quiet stance, proprioception (combined with touch by the feet) is the modality with the lowest sensitivity thresholds.

J. J. Jeka et Lackner (1994) amongst many others study the influence of a light contact of the finger (not providing mechanical support) with a stationary surface. It has been shown that sway was reduced during light touch of a stationary surface as much as for a touch providing mechanical support or vision. More detailed is provided in section 3.

The entire body, covered in muscles, tendons and skin is a haptic interface and by extension a kinesthetic interface. The influence of the touch of a stationary surface is

not limited to the feet or the hand but to the entire body. Studies have shown that sway is reduced when the shoulder (Johannsen, Lou, & Chen, 2014) touches a stationary reference, the neck (Krishnamoorthy, Slijper, & Latash, 2002) or the back (Saini, Burns, Emmett, & Song, 2019).

Postural control relies on the integration of sensory information from different sensory sources. The fusion of these information is not linear. The intra-modality and inter-modality information are re-weighted dynamically and can depend on the task (Assländer & Peterka, 2014 ; Bryanton, Chodan, Vander Meulen, Fenrich, & Misiaszek, 2019 ; Honeine, Crisafulli, Sozzi, & Schieppati, 2015 ; J. Jeka, Oie, & Kiemel, 2000 ; Logan, Kiemel, & Jeka, 2014 ; Oie, Kiemel, & Jeka, 2001).

### 2.2.3 Postural Coordination

As previously explained, the body is allowed many possible postures even in upright stance. As the CNS cannot control at the same time each part of the body, the important number of degrees of freedom need to be reduced (Bernstein, 1967). Different approaches, the **neuromuscular and dynamical approach**, have been proposed to explain how the different parts of the body are controlled simultaneously (see (Marin & Bardy, 2011) for a review of the different approaches).

The neuromuscular approach supported by Nashner et McCollum (1985) amongst others states that the CNS chooses and parametrises a predefined strategy based on biomechanical requirements (amplitude or frequency characteristics of a perturbation) and on the characteristics of the support surface (slipperiness, compliance, possible motion). Two main strategies arise qualified of **ankle and hip strategies** with an impressive amount of mixed strategies in between. The ankle strategy usually observed during non-perturbed quiet stance can be summarized as a movement of the entire body around the ankles. The inverted pendulum model is based on this ankle strategy. The hip strategy can be summarized as the simultaneous movement in opposite directions of the ankle and hip joint. The double inverted pendulum model takes into account the existence of such hip movements.

The dynamical approach explains that as the body is a system with many interacting sub-systems, rather than the CNS choosing from a range of predefined strategies, the **coordination strategy observed is the optimal result of the interaction, and not a sum, of constraints**. Intrinsic or individual constraints, environmental constraints as well as task-related constraints are considered and "weighted" to organise movement to answer a specific need (Newell, 1985).

Marin et Bardy (2011) explain that Preferential coordinations arise from this organisation that can be quantified or qualified based on how the different body segments are in phase. **In-phase coordination** qualify a movement of the hip and ankle in the same direction, the observation of an in-phase movement is similar to an ankle strategy. A movement of the ankle and hip joints in opposed directions is said in **anti-phase**. This appears from an observation point of view to be a hip strategy. While preferential coordinations exist, many other coordinations exist with lead or lag phase. The transition relies on the evolution and "reweighting" of the different constraints.

Zhang, Kiemel, et Jeka (2007) explain that in-phase and anti-phase movements of the trunk and leg segments coexist in quiet stance. The predominant use of in-phase and anti-phase movements is frequency dependant. In-phase movements are predominant for frequencies below  $1Hz$  while anti-phase above  $1Hz$ . The investigators explain that the addition of sensory information (vision and light touch) affects the frequency below  $1Hz$  (mostly in-phase) with an increase of anti-phase movements. The co-existence of in-phase and anti-phase movements as well as the structuring of the variance of the different joints reflects that quiet stance is the result of the interaction of biomechanical and neural control (Zhang et al., 2007).

Hsu, Scholz, Schöner, Jeka, et Kiemel (2007) investigated the effect of the variance of the different segments on Center of Mass and head positions using the Uncontrolled Manifold Theory. They found that the different joints (6 in their study) were coordinated so that their combined variance would have minimal effect on the important variables of postural control (COM and head movements). They found that when vision was removed, the different joints variance were increased but a change of coordination (different structuring of the variance) led to only little changes in terms of stability of the COM and head position.

While the double or multi-joints inverted pendulum seems to be better suited to study postural control (Kiemel, Zhang, & Jeka, 2011), Zhang et al. (2007) explain that in the AP direction, in quiet stance, a single-joint inverted pendulum might be sufficient as most of the sway is at low frequencies (well below  $1Hz$ ).

### 3 Light Touch and Light Grip for Postural Control

As previously explained, postural control relies on the integration of sensory information. These information are used by the CNS to estimate the position and movement of the body in space. The stabilization of the body includes sensory based biofeedback using anticipatory adjustments.

Light Touch can be described as standing upright while lightly touching a surface with the finger in a non-supportive manner. [J. J. Jeka et Lackner \(1994\)](#) introduced the notion of Light Touch for a touch with a normal force inferior to 1N to differentiate a Touch that provides mechanical support from a Touch that does not. Light Grip can be described as standing upright while lightly gripping a stick or the handle of a cane in a non-supportive manner. It was, to our knowledge, introduced by [J. J. Jeka, Easton, Bentzen, et Lackner \(1996\)](#).

Sway variability (COP or COM displacement or velocity amplitude) is reduced with Light Touch compared to No Touch ([Backlund Wasling, Norrsell, Göthner, & Olausson, 2005](#); [Clapp & Wing, 1999](#); [Holden, Ventura, & Lackner, 1994](#); [J. J. Jeka & Lackner, 1994](#); [Krishnamoorthy et al., 2002](#)). The reduction is greater when the touch is in the direction of the greatest instability ([Rabin, Bortolami, DiZio, & Lackner, 1999](#)) and in more challenging situations such as with eyes closed and on foam ([Dickstein, Shupert, & Horak, 2001](#)). The change in oscillations observed for the Light Touch have also been observed for Light Grip ([Albertsen, Temprado, & Berton, 2010](#); [J. J. Jeka et al., 1996](#); [Sozzi, Decortes, Schmid, Crisafulli, & Schieppati, 2018](#)).

The hypothesis that the influence of Light Touch and Light Grip on sway could be explained by a **mechanical stabilisation, has been rejected** by many in the literature. [Holden et al. \(1994\)](#) showed that only 2.3% of the reduction of sway in presence of Light Touch could be attributed to a mechanical stabilization. Even if such a mechanical stabilisation was possible, studies showed that the reduction afforded by a touch that could provide mechanical support was not greater than the one with a light touch ([J. J. Jeka & Lackner, 1994](#); [Sozzi et al., 2018](#)). Studies showed that sway was reduced with non-rigid touches (pulley system in ([Krishnamoorthy et al., 2002](#)), cables linked to the ground in ([Mauerberg-Decastro et al., 2014](#)) or flexible filaments ([J. Lackner, Rabin, & DiZio, 2003](#))) or even an air stream under the finger ([Backlund Wasling et al., 2005](#)). This highlights the sensory information. This is in line with a study of [Kouzaki et Masani \(2008\)](#) showing that there is no effect of Light Touch if the sensory feedback is prevented but the mechanical stabilization is not hindered.

### 3.1 The Information and Facilitation Hypotheses

If this influence is not mechanical. How can it be explained? Two main hypotheses explain the reduction of sway in presence of Light Touch or Light Grip in quiet stance.

The information or sensory hypothesis explains that Light Touch/Grip provides sensory information used to reduce sway. The supra-postural or facilitation hypothesis explains that sway is reduced to facilitate touch, to answer the precision demands of the task.

What does these two hypotheses imply ?

- The information hypothesis implies that touch provides **sensory information** about sway and that a reduction of sway is equivalent to a stabilization. This hypothesis does not imply that sway is minimized, simply that it is reduced. Whether attentional demands used to reduce is however unclear.
- The facilitation hypothesis implies that sway is reduced to touch. It does not imply that the information provided can be used to estimate sway nor the contrary. As light touch becomes a **supra-postural task**, it implies that attentional resources are used.

These two hypotheses do not have to be contradictory. [Lee, Pacheco, et Newell \(2019\)](#) or [Rabin, DiZio, Ventura, et Lackner \(2007\)](#) explain that Light Touch can provide information to reduce sway while adding a supra-postural task, a precision task whose execution is facilitated by the decrease of sway.

The hypothesis combining the two can be expressed as follows. **Touch provides sensory information about body motion while adding a supra-postural task.** Touch cues can be used to reduce and this reduction is facilitating the touch. This can be seen as a "virtuous" perception-action loop. Like for both hypotheses, there is no need for the reduction to be associated with a minimization. The study of Light Touch and Light Grip is presented to highlight the sensory cues provided by the contact. Investigations highlighting the facilitation of touch by a reduction of sway are presented further in the State of the Art.

The main consensus concerning the sensory cues provided by Light Touch/Grip explains that Touch/Grip provides an **anchor in space**, a source of sensory information **closer to the COM**. It is likely that Light Touch/Grip provides information about the position and velocity cues of body sway, in other words, an **external stationary reference** in space and **movements cues** through the changes in shear forces. The name Light Touch might lead to think that only tactile information are important however, studies show that tactile cues need to be integrated with proprioceptive information of the arm and body in order to be used.

### 3.2 Is Light Touch Equivalent to Light Grip ?

Light Grip for postural control is investigated in this thesis. However, many studies in the literature focus on the influence of Light Touch. It seems relevant to question whether then can be seen as similar and if results concerning Light Touch can be extended to Light Grip.

Sozzi et al. (2018) found that the reduction of COP oscillations was similar with LT (Light Touch of the finger) and LG (Light Grip of an inclined cane) compared to No Contact (NC) for blind participants (They found no difference between blind participants and participants with eyes closed). They also found no difference between LT and LG for the latency to reach steady state (NC  $\leftrightarrow$  LT and NC  $\leftrightarrow$  LG) implying that object-mediated touch does not significantly modify the time needed to process the information compared to direct touch.

These findings support the idea that **studies about light touch are relevant for the study of Light Grip**. However, other considerations must be kept in mind such as the overall sensitivity of the skin in contact might be different as a wider area is in contact for the Light Grip but also the palm which as a lower sensitivity.

### 3.3 Sensory Information and the Effect of Light Touch and Light Grip

#### 3.3.1 Light Touch with an Increased Sensitivity

A study by Magalhães et Kohn (2011) showed that by increasing the tactile sensitivity of the finger (through the addition of vibratory noise) during Light Touch, a greater decrease of COP oscillations could be observed with the vibrating Light Touch than with Light Touch without vibration. This suggests the reduction of sway depends on the sensory information and cannot be explained only by a supra-postural facilitation.

#### 3.3.2 An External Stationary Reference and Transient Cues of Sway

Light Touch/Grip likely provides sensory information through the deformation of the skin, related to the changes in transient forces of contact as well as the location of the point of contact. Studies used **modulation of the transient forces** of contact and played with the **presence of a stationary external reference** to study the influence of Light Touch/Grip.

**Sway is reduced in the presence of transient cues of sway even in the absence of an external stationary reference** Different studies showed that sway was reduced with Light Touch/Grip even in absence of a stationary reference if they were transient cues of sway ([Albertsen et al., 2010](#) ; [Krishnamoorthy et al., 2002](#) ; [Mauerberg-Decastro et al., 2014](#)).

[Albertsen et al. \(2010\)](#) compared Light Grip of a fixed or mobile stick touching the ground. They found that sway was reduced with both mobile and fixed sticks. They used a block at the tip of the stick, by constraining the movement of the stick on the ground, it provided more information to the participants compared to without the block. They also used a slippery surface to limit the amount of information compared to the rough surface. They also found that the reduction was greatest when the touch provided more information regarding the movement of the body (greater reduction with the block and absence of reduction with the slippery touched surface).

[Krishnamoorthy et al. \(2002\)](#) compared the influence of different kinds of Light Touch on the displacement and velocity of COP oscillations. They used a pulley system to test the influence of transient cues of sway without the reference position. They found that COP oscillations in terms and displacement or velocity amplitude were reduced even in absence of a external reference position if transient cues were present.

[Albertsen et al. \(2010\)](#) and [Krishnamoorthy et al. \(2002\)](#) explain that the mechanoreceptors provide information on the position of the point of contact (Slowly Adapting receptors) and on the speed, direction and amplitude of the oscillations (Rapidly and Slowly Adapting receptors).

**Sway is reduced in the presence of an external stationary reference even with very little skin-deformation** [Backlund Wasling et al. \(2005\)](#) showed that COP oscillations could be reduced with an external stationary reference even when very little shear force is present or skin deformation is present. They studied the relative contribution of two kinds of somatosensory or haptic information on sway. They compared two kinds of light touch : a rigid rod glued to the tip of the finger and an air stream on the finger. The rod providing information about friction-induced changes in skin-stretch (stationary reference and transient cues of sway) and the air stream providing spatio-temporal information (mostly an external reference). They found that the Light Touch with a glued rod induced a decrease of the amplitude of sway and of the path of sway where the air stream induced a decrease of the amplitude only. The amplitude reflects for a big part the low-frequency components of the signal whereas the path reflects for a big part the high frequency components of the signal. This experiment highlights that the spatial variation of the point of contact without shear force is sufficient to reduce

sway. The variation of the point of contact could be assimilated to an information about the position but without or very little information about the velocity.

J. Lackner et al. (2003) used flexible and rigid filaments as touched surfaces. The flexible filaments as the air stream do not provide a precise shear information feedback. They found similar conclusions. Sway was reduced to a lesser extent with the flexible filaments compared to the rigid filaments.

J. J. Jeka et Lackner (1995) compared the light touch of a rough or slippery surface. Both provided an external stationary reference but the slippery surface induced a decrease of the skin deformation and thus of the transient cues of sway. They found that sway was reduced with Light Touch on both surfaces.

**The Direction of the cues** J. J. Jeka et al. (1996) showed that the reduction with Light Grip is greatest when the haptic cues are preferentially in the direction of sway. They compared the influence of the Light Grip of a vertical and slanted cane for blind participants in tandem-romberg stance. This is in line with the idea that the influence of Light Touch is greatest when in the direction of the greatest instability (Rabin et al., 1999).

### 3.3.3 A External Reference Closer to the Center of Mass

Studies show an increased **hip use** during Light Touch (Zhang et al., 2007). Franzén, Gurfinkel, et Wright (2011) explain that a **local reference frame closer to the COM** is used to integrate the light touch information. This is in line with the study of Assländer, Smith, et Reynolds (2018) that showed that the integration of the light touch sensory information was not integrated as an angle around the ankle but as a distance to the COM.

### 3.3.4 Multi-sensory Integration of Light Touch

**Sensory re-weighting for postural control in general** Studies using moving light touch whether it was slow oscillatory motion or sudden rapid movements highlight the use of the information provided by light touch as well as the fact that the integration with other modalities is non-linear and depends on the task and context.

Assländer et al. (2018) studied pseudo-random movements of the surface light gripped. They found that the increase of the movement of the COM was not linearly related to the increase of the movement of the hand. The modification of sway amplitude was of



lesser magnitude for greater finger motion. The authors conclude that a **re-weighting of the cues** likely happened for greater amplitudes using cues from other modalities.

Other studies use rapid movements of the touched surface (Bryanton et al., 2019 ; J. Misiaszek, Forero, Hiob, & Urbanczyk, 2016 ; J. E. Misiaszek, Chodan, McMahon, & Fenrich, 2020). The aim of these movements is to make the information provided by Light Touch unreliable but not destabilizing enough to require reflex corrections. Bryanton et al. (2019) showed that possibly unreliable touch cues are not simply down-weighted in favor of another modality but that information about body sway can likely be extracted by learning how the perturbation affected them. This study highlights that the **flexibility of the integration** of light touch cues that is **adapted to the context and the task at hand**.

**Light Touch and Proprioception** The integration of Light Touch cues are intertwined with the integration of proprioceptive cues. Rabin et al. (1999) explain that the effect of light touch is greater in the plane of greater instability. Caudron, Nougier, et Guerraz (2010) showed that the effect of a vibration of the Achilles tendon, disturbing kinesthesia was reduced with Light Touch. Rabin et al. (2007) highlight the importance of a **correct proprioceptive information** (correct estimation of the configuration of the arm) for the integration of tactile cues. The investigators also explain that a precision touch is not necessary to observe a reduction of sway with Light Touch. This was also showed by Krishnamoorthy et al. (2002) where sway was reduced with a light touch on the neck.

**Light Touch and Vision** J. J. Jeka et Lackner (1994) and Clapp et Wing (1999) compared the effect of Light Touch to the effect of Vision in the ML direction in tandem-romberg stance and in feet apart stance in AP direction respectively. They found the reduction of the amplitude of the COP to be similar between Light Touch alone and Vision alone and that the reduction of COP oscillations was greater with both.

Backlund Wasling et al. (2005) compared two kinds of light touch : a rigid rod glued to the tip of the finger and an air stream on the finger and vision. The rod providing information about friction-induced changes in skin-stretch and the air stream providing spatio-temporal information. They found that the Light Touch with a glued rod induced a decrease of the amplitude of sway and of the path of sway where the air stream induced a decrease of the amplitude only and vision a decrease of the path only. They found a combination of the effects when vision and touch were together. The effect of vision and air-stream on the CoP oscillation and COP trajectory in the AP-ML plane is visible in Figure 6.

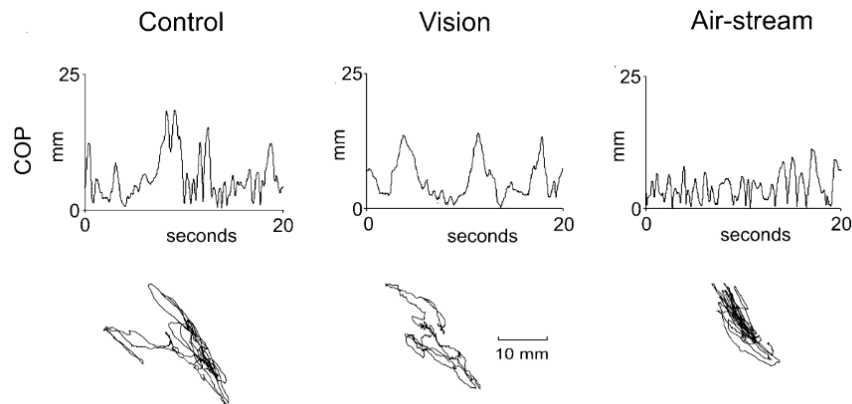


FIGURE 6: COP oscillations in the AP direction and trajectory on the support surface for the control, vision and air-stream conditions in (Backlund Wasling et al., 2005). We can see that for the air-stream, mostly high frequencies are visible while low-frequencies are visible for vision.

As previously proposed, the amplitude reflects for a big part the low-frequency components of the signal whereas the path reflects for a big part the high frequency components of the signal. Vision had the opposite effect of the air stream highlighting that **vision may provide velocity information and not positional information**. J. Jeka, Oie, Dijkstra, Schöner, et Henson (1998) explain that the optical flow most likely defines a velocity reference frame and not a spatial reference frame. Light touch (represented by the glued rod) would provide both a stationary reference and transient cues of sway (velocity-like information).

The impact of oscillatory movements of the touched surface were also studied in presence of oscillatory movements of the visual scene. Oie et al. (2001) found that there was a **intra-modality and inter-modality re-weighting** as the impact of the visual movement depended on the amplitude of movement of the visual scene as well as the amplitude of movement of the touched surface and that the impact of the touched surface depended on the amplitude of the movement of the touched surface as well as the amplitude of the movement of the visual scene. These weights are considered to be adapted continuously depending on the different cues and context. Furthermore, it was shown that the re-weighting was not an additive process but a non-linear one (J. Jeka et al., 2000 ; Oie et al., 2001).

### 3.3.5 Anticipation

In this thesis, we study the use of Light Grip sensory information for the voluntary control of sway as well as the Light Grip in relaxed stance. As highlighted by Loram et al. (2001) for instance, the regulation of balance encompasses anticipatory adjustments.

We will thus briefly discuss findings in line with an anticipatory use of Light Touch/Grip cues.

The Feedforward mechanisms at play during Light Touch are highlighted by the reduction in sway in patients with Peripheral Neuropathy (Dickstein et al., 2001). Peripheral neuropathy can be, in part, characterized by delayed, distorted and/or absent somatosensory information from cutaneous, joint and muscle receptors of the feet and legs. Given the increase of the delays of transmission, a reduction can only be explained by a **feedforward mechanism** using the sensory information provided by Light Touch.

These mechanisms can also be highlighted thanks to the use of perturbations such as kinesthetic perturbations using proprioceptive-driven illusions (muscle belly or tendon vibrations) or mechanical.

The reduction or suppression of kinesthetic perturbations with Light Touch compared to without it (J. R. Lackner et al., 2000) shows that the light touch cues can likely be used to **anticipate a perturbation**. Correct knowledge of the configuration of the arm appears crucial in the integration of Light Touch cues as they are necessary to disambiguate the origin of the movement. The anticipation and adaption seems however to be **context dependent**. Caudron et al. (2010) showed that it depended on how threatening the perturbation was.

Johannsen, Wing, et Hatzitaki (2007) used arm mechanical perturbations (voluntary and reflex) during light Touch with the shoulder. The investigators found that the stabilization after the perturbation was faster with Light Touch and that the effect of Light Touch was greater for the voluntary pull suggesting a **predictive use of Light Touch cues**.

### 3.4 The Supra-postural Task

The effect of Light Touch is associated by researchers to the constraints added by the supra-postural task. The reduction of sway would be to facilitate touch. This hypothesis does not exclude that touch provides information usable to reduce sway depending on the task but why sway is reduced.

Studies have shown that sway can be reduced to facilitate light touch.

M. Riley et al. (1999) questioned whether the reduction of sway observed with Light Touch is due to the addition of a supra-postural task. They compared the influence of two kinds of touch on postural sway in presence of Light Touch. They asked participants to either maintain contact with a curtain and to prevent its movement or to stand while

touching without minding the touch. They found that sway was reduced only in the condition where the contact was said relevant to the participants. The authors concluded that the reduction of sway observed with Light Touch could be explained by the addition of a supra-postural task. **Control is facilitating the touch by reducing sway.** The authors do not reject the idea that touch provides information but rather the idea that sway needs to be reduced to stabilize the body.

Using a concurrent cognitive task (reaction time task), it has been shown that maintaining this precise contact with the curtain is **attention demanding** (Vuillerme, Isableu, & Nougier, 2006)). However, if the task can be facilitated by a reduction of sway, such as a visual search then sway with Light Touch can be reduced further with Light Touch and the cognitive task (dos Santos et al., 2019). This highlights the difference between supra-postural tasks. While some can be facilitated by a reduction of sway, others likely cannot be.

Mcnevin et Wulf (2002) explained that maintaining a precise contact could be associated with an external focus of attention. When participants are asked to maintain a light contact, their focus is shifted. Asking Participants to lightly touch or lightly grip shift their attentional focus to the effect of their movement : the movement of the curtain in the study presented or an auditory cue in many protocols with Light Touch. McNevin et al explain that an **external focus** likely promotes a more efficient and automatic control of sway.

While the supra-postural task of maintaining a light touch or lightly gripping can be seen as helping the reduction of sway, in case of perturbations, the constraint added can hinder the control of postural by complicating the planning of the movement (Johannsen et al., 2007) or requiring a precise contact during a perturbation (Rabin et al., 2007).

Studies show that if the precision demands of the light touch are increased, sway can be further reduced compared to the less precise touch (Lee et al., 2019). Furthermore, the reduction of sway with the increased precision demand is greater if participants are more sensitive tactile-wise (Chen, Pan, Tu, Tsai, & Li, 2017). These studies show that a reduction can facilitate touch and that touch provides information necessary to reduce. These studies highlight how **the supra-postural task of Light Touch is intertwined with the sensory information provided by Light Touch** allowing the reduction with the precision task (Lee et al., 2019).

### 3.5 The Study of Light Touch in the Frequency Domain

Only a few studied to our knowledge investigate the influence of Light Grip in the frequency domain. As Light Touch/Grip provides an external stationary reference (very low frequency) and transient cues of sway (low frequency), frequency analysis could reveal the impact of Light Touch/Grip on the whole sway spectra.

[J. J. Jeka et al. \(1996\)](#) plotted the power spectra for No Grip, Light Grip with a slanted cane and Light Grip with a vertical cane in different frequency bins between 0 and  $1Hz$ . While the authors only discussed the overall differences of the Slanted and Perpendicular Grip in the frequency domain, we can see from their plots that the power is not affected homogeneously over frequencies by the two Grips. There is a greater reduction of power for the slanted cane compared to the perpendicular one but the difference is especially visible for the low frequencies as can be seen in Figure 7. The slopes across the bins are different for the two Grips.

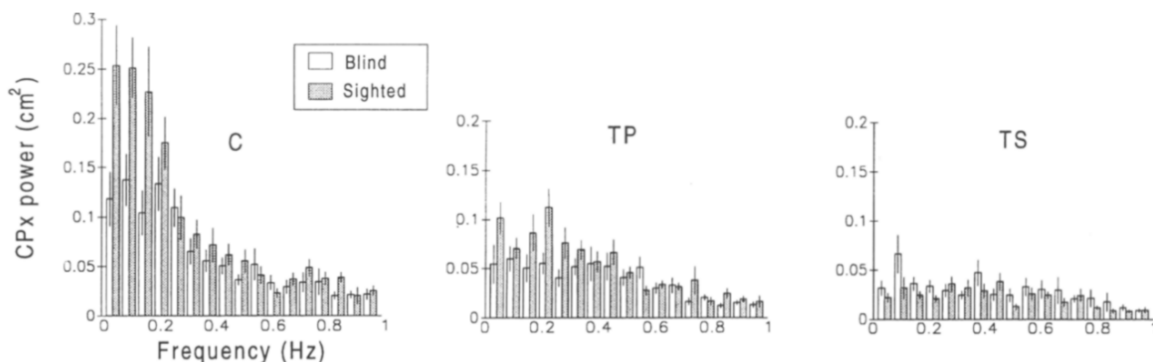


FIGURE 7: Mean Power over frequency bins for : without Grip (C), Slanted Grip (TS) and and Perpendicular Grip (TP) extracted from ([J. J. Jeka et al., 1996](#))

The effect of the addition of Vibratory noise to Light Touch was studied by [Magalhães et Kohn \(2011\)](#). They plotted the power spectra (PSD) and computed the power (area under PSD) on different frequency bands. The Low Frequency band ( $< 0.5Hz$ ) roughly corresponds to the sway of the body and the other band corresponds to the remaining frequencies ( $0.5 < f < 2Hz$ ). The Low frequency band was affected by the addition of noise to Light Touch and by Light Touch while the high frequencies were not. This highlights that the frequency content is not homogenous across frequencies and that it is also not affected homogeneously.

[Backlund Wasling et al. \(2005\)](#) used the path and the amplitude. These are time-domain measures but they provide information on different frequency content. This study provides indirectly information regarding the reduction of very low and higher frequencies of COP oscillations.

Some studies use windows of roughly 1s to investigate the influence of Light Touch without comparing the position of the windows. The influence of the non-stationarity of the signals is prevented. However, this prevents the analysis of the influence of Light Touch on very low frequencies that are quite substantial in sway patterns. We can hypothesise that the effect of a stationary reference in absence or in presence of only little amount of transient cues would not be detected with such windows (a touch on a curtain is likely providing a reference more than anything else).

Finally, we would like to comment briefly on the use of the median frequency to study Light Touch. This index provides information about the frequency content of sway in terms of increase/decrease between conditions. However, it does not give any information regarding the distribution of the power that is considered not homogeneous [Bensel et Dzendolet \(1968\)](#) and that might lead to faulty conclusions. Indeed, an increase of the median frequency can be explained either by an increase of high frequencies or a decrease of low frequencies accompanied by decrease of lesser magnitude in the high frequencies. For example, an increased median frequency, caused by a huge decrease of low frequencies (usually associated to a better control) could be interpreted as a deteriorated postural control (increase of high frequencies). The substantial influence of Light Touch/Grip on low frequencies would suggest that the median frequency would be increased while the frequency content is decreased. This was investigated using the data of the study presented in Chapter 4. The results are presented in the appendix B.

## 4 Biofeedbacks for Postural Control

### 4.1 Biofeedbacks : A brief Introduction

#### 4.1.1 Biofeedbacks for Balance

A biofeedback system for balance aims at improving postural control. [Sienko et al. \(2018\)](#) provide a clear definition : "We define SA" (active Sensory Augmentation devices) "as **the delivery of additional sensory cues (e.g., via auditory, tactile, or visual modalities) that convey pertinent information about body orientation for balance**". Biofeedbacks can be used in real-time or after the execution of the task. We will only discuss real-time biofeedbacks in this thesis.

Sensory deficits or aging can lead to an increased risk of falling. These falls, in many cases, can cause injuries that induce a reduced mobility and reduced independence. Biofeedbacks have been studied to help people regain independence and mobility.

While part of the studies include patients, elderly fallers and not fallers, many studies focus on the design of biofeedbacks with young and healthy participants even if they are not considered to be the end-users. Many non-clinical studies focus on the use of biofeedbacks in quiet and perturbed stance.

Many study the effect of Biofeedbacks for a reduction of variability in mind may it be in terms of COP or COM amplitude of oscillations, velocity or acceleration.

#### 4.1.2 Technical Overview

The way these devices function can be described in three steps : (1) monitoring, (2) coding and (3) transmitting. They monitor physiological signals such as the angle of the body or the position of a limb and feed it back to the individual through a sensory channel once the signals are encoded in order to be meaningful and understandable by the individual. These three steps need to be considered in the design and study of biofeedback devices.

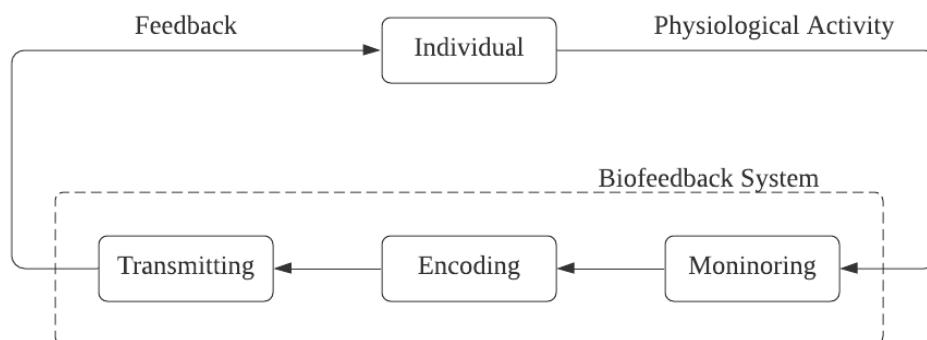


FIGURE 8: Biofeedback Flowchart

Numerous studies find that sway can be reduced using various kinds of biofeedbacks (Alahakone & Senanayake, 2010 ; Ballardini et al., 2020 ; Dozza et al., 2005) amongst many. The inputs, encodings and outputs used are various. Some studies find however no effect of biofeedback or only very little (Danna-Dos-Santos, Degani, Zatsiorsky, & Latash, 2008 ; Pan, Yoon, & Hur, 2017) amongst other.

#### 4.1.3 Mechanism at Play

The mechanisms at play in the process and use of biofeedbacks remain unclear despite numerous studies on the use of biofeedback for balance.

As previously explained, sensory information from the different sensory channels are integrated by the CNS to estimate the position and motion of the body in space in order to chose the adapted motor commands to maintain balance.

Biofeedback devices provide information regarding the position/movement of the body in space. Whether the information provided was already in possession of the CNS or not does not change the fact that sensory information regarding balance is provided.

Different hypotheses are proposed to explain how these information are used. [Sienko et al. \(2018\)](#) briefly reviews different hypotheses.

The predominant hypothesis explaining the effect of biofeedback devices is that the information provided by the Biofeedback is used by the CNS to **re-weight** the "native" sensory information. The information fed back by the biofeedback system is likely giving more weight to the "native" sensory information that is correlated with the biofeedback information.

Other hypotheses propose that the information is not used in the sensory-reweighing process. The information is added and used voluntarily by the individual (user/participant) through a **cognitive process**.

## 4.2 Biofeedbacks : Monitoring, Encoding and Transmitting

The choice of the input, of the encoding and output of the biofeedback system are far from independent and must be considered together. However, to alleviate the presentation, the different steps will be presented separately. In order for the following parts to be relevant, we would like to quickly summarize them.

- Outputs or sensory interfaces : Vision, Hearing, Touch ;
- Inputs : Position, Velocity, Acceleration or combination of several of those, of COP, COM, trunk angle, or even head position ;
- Encoding : Alarm when a threshold is reached, Amplitude of the variable, Direction (*e.g.* forward/backward sway or leftward/rightward sway) or combination of those.

The information fed back must be chosen carefully to answer a specific need and must be coded in order to be understandable and conveyable. The intelligibility of the biofeedback depends on the information chosen and its encoding. The intelligibility is necessary but does not imply that it can be used by the individual. The encoding is directly related to the amount of information transmitted.



Before discussing the different biofeedbacks for balance, we would like to note that the effect of a biofeedback depends on the **instruction** given to the individual using it. If the objective of the study of the biofeedback is to observe to what extent a participant is able to minimize his/her sway, the instruction must be chosen accordingly. If a participant is asked to stand in a no-feedback zone, for a vibrotactile or audio biofeedback for example, but the task is not very demanding, it is possible that the participant had still the possibility to reduce more and asking him/her to minimize would have led to different results. While the instruction to cancel the feedback might not be always well-suited to test the minimization of sway, it may present the advantage of adding an external focus of attention rather than an internal focus, promoting perhaps a more automatic control (Wulf & Prinz, 2001).

### 4.3 Biofeedback Output or the Sensory Interface

These information can be conveyed through different sensory channels : The Visual Channel, the auditory channel and the haptic channel. Amongst many, Dault, de Haart, Geurts, Arts, et Nienhuis (2003), Lakhani et Mansfield (2015), Caudron et al. (2014) or Rougier (2003) study visual biofeedback. We can cite, amongst many, studies from Dozza et al. (2005) ; Dozza, Chiari, Peterka, Wall, et Horak (2011) for auditory-biofeedback. We can cite amongst many studies on tactile biofeedbacks, studies by Alahakone et Senanayake (2010) ; Ballardini et al. (2020) ; Sienko, Balkwill, et Wall (2012) ; Wall et Kentala (2010) or Gopalai et Arosha Senanayake (2011). Some studies investigate the use of multimodal biofeedback like Bechly, Carender, Myles, et Sienko (2013) or Davis et al. (2010).

The choice of the sensory channel conditions the amount and kind of information conveyable. While they are different, all modalities are well suited to provide information in terms of direction or amplitude.

The biofeedback device provides an information about the presence of the body in space but the information is coded and transmitted through a modality. We would like to point out that the use of a biofeedback using one modality cannot infer on the use of the said modality in general for postural control as cognitive processing, integration or other processes might be different.

Tactile biofeedbacks are usually preferred for their **little invasiveness** as they do not interfere with other daily life tasks such as talking, eating, seeing or hearing as well (Alahakone & Senanayake, 2010 ; Loughlin, Mahboobin, & Furman, 2011). Furthermore, aging and balance deficits such a vestibular deficits can be accompanied by visual or hearing deficits. Tactile biofeedback are not subject to such deficits. Finally, the whole

body is covered in skin, even if the sensibility is not homogeneous on the whole body, the body offers a great variety of stimulation sites.

Visual biofeedbacks contrary to tactile biofeedbacks can be used efficiently to convey information of direction and amplitude but vision can be used to convey "a bigger picture". We can easily imagine a visual biofeedback providing information used to bring the participant hand or body to a specific position. The history of the position of the COP or COM for example can be easily provided with the visual modality unlike the other modalities.

Different kinds of tactile biofeedback exist including skin-stretch feedback, the skin can be stretched with a chosen direction and amplitude (Husman, Maqbool, Awad, & Abouhossein, 2016 ; Pan & Hur, 2017 ; Pan et al., 2017) ; eletrotactile feedback, the skin or tongue is electrically stimulated (Tyler, Danilov, & Bach-Y-Rita, 2003 ; Vuillerme, Chenu, Demongeot, & Payan, 2006) and vibrotactile biofeedback (Goodworth, Wall, & Peterka, 2009 ; Gopalai & Arosha Senanayake, 2011 ; Janssen, Stokroos, Aarts, van Lummel, & Kingma, 2010 ; Kentala, Peterka, & Wall, 2006) used in our study.

With vibrotactile feedback, the skin is vibrated at a chosen amplitude and frequency. In many studies, the trunk is vibrated using a belt of vibrotactile actuators that can be activated independently or together. Other stimulation sites exist (the back in (Saini et al., 2019) for example). Vibrotactile devices are relatively easy to setup and can be made portable and are more easily accepted than electrotactile devices.

In this study, we are interested in tactile biofeedbacks. Studies compare the different modalities for biofeedbacks for balance and study the use of multimodal biofeedbacks. We can mention the study from Bechly et al. (2013) showing that if the same amount of information is provided by two different modalities (visual and vibrotactile), the trunk tilt is reduced similarly. This study suggests that studies of audio or visual biofeedbacks can be useful to study tactile biofeedbacks.

#### 4.4 Biofeedback Input or Biological Input Monitoring

The use of a biofeedback system entails the monitoring of meaningful physiological signals using sensors. The signals to monitor must be chosen carefully. The choice of the signal to monitor influences the use of the biofeedback even though after processing, signals of different origins present redundancies.

#### 4.4.1 Postural indexes

Different body sway indexes are used in the literature. They all come with advantages and drawbacks.

- Center of Pressure ([Lakhani & Mansfield, 2015](#)), [Rougier \(2003\)](#), [Pan et al. \(2017\)](#), [Dault et al. \(2003\)](#)) or Center of Mass ([add citations](#) measurements using Force Platforms and motion capture systems are considered accurate and reliable. However, these systems are not portable and in most cases expensive.
- Trunk angle ([Ballardini et al., 2020](#) ; [Gopalai & Arosha Senanayake, 2011](#) ; [Sienko, Vichare, Balkwill, & Wall, 2010](#)) or movement of the head [Danna-Dos-Santos et al. \(2008\)](#) ; [Davis et al. \(2010\)](#) using Inertial motion sensors (accelerometers, gyroscopes and magnetometers) or pressure distribution using force sensors in the shoe-soles ([Ma, Wan, Wong, Zheng, & Lee, 2014](#)) are low-cost compared to force platforms and mocap systems and can be made portable, they can be "wearable-sensors".

It appears that force platforms and mocap systems present various advantages for research of postural control mechanisms but are ill suited for clinical purposes.

Different studies compared the use of different postural indexes. Several studies show that both COP and COM can be used effectively with very similar results ([Halická, Lobotková, Bučková, & Hlavačka, 2014](#) ; [Kilby, Slobounov, & Newell, 2016](#) ; [Lakhani & Mansfield, 2015](#)). Other studies propose combinations of the COP and COM ([Kilby, Molenaar, Slobounov, & Newell, 2017](#) ; [Takeda et al., 2017](#)) that can be used to reduce sway.

#### 4.4.2 Dimensionality of the Signal Used : Position, Velocity, Acceleration ?

The system used to monitor defines the dimensionality of the signal. For example, the COP extracted from force platform data represents the position of a point of application while an accelerometer on the trunk provides the linear acceleration of the trunk. However, these signals can be processed. The encoded information can be based on position ([Alahakone & Senanayake, 2010](#) ; [Danna-Dos-Santos et al., 2008](#) ; [Gopalai & Arosha Senanayake, 2011](#)), velocity or acceleration ([Ballardini et al., 2020](#) ; [Dozza et al., 2005](#)) signals to drive biofeedback devices. Sometimes, a combination of different signals is used ([Goodworth et al., 2009](#)).

[Loughlin et al. \(2011\)](#) in line with experimental results of [Goodworth et al. \(2009\)](#) explain that different combinations of position and velocity have been studied to drive vibrotactile biofeedbacks. The effect of the different combinations is not homogeneous

across frequencies. As can be seen on the Figure 9, a position-driven biofeedback would tend to decrease the low-frequency content of sway while increasing the high frequency content. As velocity is combined with increasing importance, the reducing effect on low frequencies is attenuated as well as the increase of the high frequency content. The investigators explain that an increased low frequency content is desirable while the increase of the high frequency content is not.

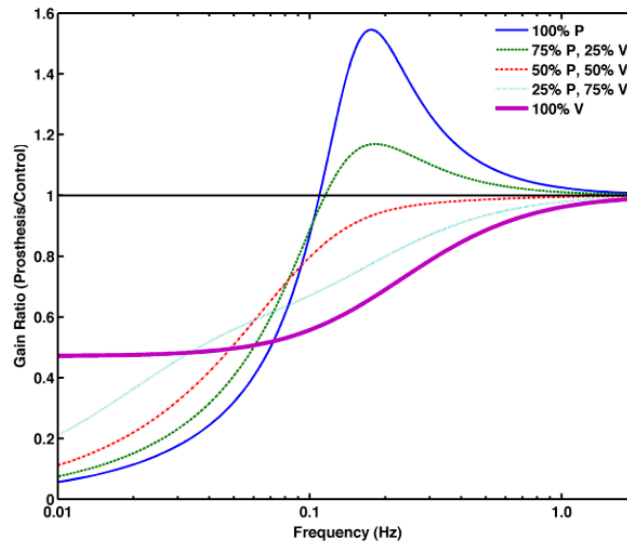


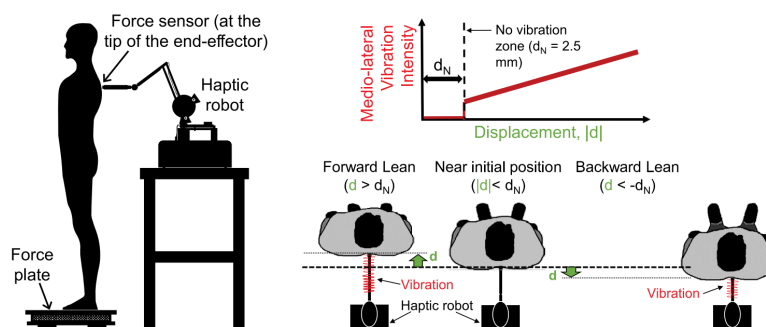
FIGURE 9: Part of the Results of Loughlin et al from [Loughlin et al. \(2011\)](#). This figure represents the gain response to the biofeedback during oscillatory support surface movements. A gain between 0 and 1 indicates a decrease with the biofeedback compared to without and a gain superior to 1 an increase.

The increase of high frequency content of the COP was also shown by [Halická et al. \(2014\)](#). They showed that the feedback that reduced the most the low frequency content ( $[0.02 - 0.3Hz]$ ) was the one that increased the most the high frequency content ( $[0.5 - 1.4Hz]$ ) of COP oscillations.

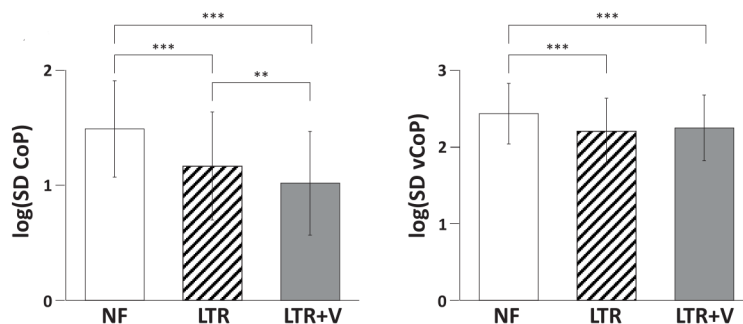
This is in line with results of [Sienko et al. \(2010\)](#). They found that trunk tilt low frequency power (using PSD estimates) was greatly reduced than the high frequency power with a vibrotactile biofeedback.

In our study, we investigate the use of a vibrotactile biofeedback with Light Grip or without Light Grip. [Saini et al. \(2019\)](#) use of position-driven vibrotactile biofeedback combined with a light touch on the back (around Th4) in the AP direction. The light contact is via a robot that "follows" the participant sway in order to not apply more than  $1N$ . The investigators explain that their light touch is providing velocity related information (due to friction in the robot joints) while the biofeedback is providing

position-related information. The vibration was the same for Anterior and Posterior sway. Their setup is presented in Figure 10A.



(A) Experimental Setup of Saini et al from Saini et al. (2019) with the robotic velocity-related Light Touch and position-relation Biofeedback.



(B) Results of Saini et al. (2019) with the effect of Light Touch and Biofeedback on COP displacement and COP velocity

FIGURE 10: Experimental Setup and Results of Saini et al. (2019)

In short they found that the position-driven biofeedback reduced only the amplitude of the displacement while the Light touch (velocity information) reduced both the amplitude of the displacement and velocity of the COP. Finally, the investigators further add that the effect could not be due to a supra-postural task associated with Light Touch but to the information content as participants did not have to mind the contact that was maintained by the robot.

Kilby et al. (2017, 2016) showed their participants the position of their COP, COM and other indexes but told their participant to **reduce independently of the position on the screen**. They motivate this instruction by saying that it is "arguably more natural".

### 4.5 Biofeedback Encoding or the Amount of Information

The signals are encoded to provide specific information. The amount of information provided varies from one Biofeedback device to the other. A different amount of information does not necessarily imply a different outcome when used (Dozza et al., 2011). For many tactile biofeedbacks, users/participants are provided information if the position/velocity/acceleration of COP or COM exceeds a pre-defined range usually called dead-zone.

Biofeedback devices for balance, using COP/COM measurements or trunk angle, usually provide users/participants with information regarding :

- the **amplitude** of the signal monitored, for example the amplitude of the oscillation of the COP
- the **direction** of the sway, for example, whether the participants is swaying forward/backward for the AP direction or leftward/rightward for the ML directions or the two directions. The resolution of the direction can be higher than AP or ML directions.
- feedback if the amplitude of the signal is above a certain threshold without any direction cue and modulation regarding the amplitude, this is an **alarm-like** biofeedback.

#### 4.5.1 On the Different Amounts and Quality of Information

Different studies focus on whether providing more specific information will impact differently the use of the Biofeedback. These studies can help shed some light on the use of the biofeedbacks and whether cognitive or re-weighting processes are at play.

Dozza et al. (2011) compared audio biofeedbacks providing either either feedback about the amplitude and direction of sway, about the amplitude alone, about the direction alone or an alarm if a certain amplitude is exceeded. They found that at the beginning of the experiment, that the more information was provided, the greater the reduction but this difference disappeared after a few trials.

We can question whether this similarity and effect without the biofeedback suggests that the correct native information were re-weighted thanks to the biofeedback.

Bechly et al. (2013) compared different biofeedbacks. They found that the greater the information content, the greater the reduction (visual biofeedbacks). They also found that providing the same information twice through different sensory channels (visual and vibrotactile) was not different from providing it through only one of the two. The fact

that the amount of information conditioned the amount of reduction would favor the hypothesis of the cognitive processing rather than the sensory re-weighting.

The fact that the amount of information conditioned the amount of reduction would favor the hypothesis of the cognitive processing rather than the sensory re-weighting.

The difference between the sham and salient biofeedbacks highlights the importance of the information transmitted. This is studied by [Ballardini et al. \(2020\)](#) who found that the amplitude (RMS to be precise) of the acceleration of the L5 vertebra was reduced with salient biofeedbacks but increased with the sham biofeedback. This is one of the few studied to our knowledge studying the use of a vibrotactile biofeedback in bipedal stance without foam and with a participant-specific dead-zone. The difference between the **sham and salient biofeedbacks** highlight the importance of the information transmitted.

#### 4.5.2 The choice of the dead-zone

Many vibrotactile biofeedbacks use a dead-zone, a no-vibration zone. The presence of a dead-zone is usually considered preferable as if used for a prolonged amount of time, they might lead to a sensory overload ([Alahakone & Senanayake, 2010](#)). The choice of the size of the dead-zone varies from one study to the other. While many studies use the same value for all participants, other calibrate the thresholds per participant.

Part of the studies use fixed for all participants like the 1 deg threshold for trunk tilt used by Sienko and colleagues in ([Kinnaird et al., 2016](#) ; [Sienko et al., 2012](#)) or [Dozza et al. \(2005\)](#) or the 2 deg threshold used by [Alahakone et Senanayake \(2010\)](#) or [Saini et al. \(2019\)](#) with the 2.5mm threshold.

Other studies use participant-specific thresholds. The amount of sway is highly variable between individuals. Furthermore, not all subjects are affected similarly by a change of the sensory context. [Loughlin et al. \(2011\)](#) emphasise the important of a participant-specific threshold. We can mention the study from [Ballardini et al. \(2020\)](#). They used the standard deviation of the acceleration of the trunk with Eyes Open before testing with Eyes Closed.

#### 4.5.3 Resolution of the Biofeedback Display and Attractive and Repulsive Cues

A study highlights that for a vibrotactile biofeedback, an anterior/posterior information might be sufficient for the AP direction compared to more complicated setups

(with more actuators that are neither completely in the AP or ML directions) even if they might provide more information (Sienko et al., 2010).

In case of a biofeedback device providing information on the direction of sway, different strategies are possible. It is possible to use attractive cues that "show" the participant where to go and there are repulsive cues that "show" the participants where they are and that they should go in the opposite direction. Kinnaird et al. (2016) compared the two types for a vibrotactile biofeedback device. The investigators explain that repulsive cues are a better fit when the time to learn is limited while attractive cues might be better suited in the long run.

#### 4.6 Biofeedbacks : Potential Costs ?

While many studies describe the beneficial effects of Biofeedbacks, we would like to very briefly discuss the beneficial effects as well as the potential costs accompanying the use of such devices for balance.

**Increased stability ?** Different biofeedbacks have been used in perturbed stance. Participants are disturbed using support surfaces motion for example. Several studies show that biofeedbacks improve the recovery from postural perturbations (Peterka, Wall, & Kentala, 2006 ; Sienko et al., 2012, 2010). These studies highlight an increased stability with the biofeedback. However, other studies question whether stability is increased with a biofeedback. Kilby et al. (2016) tested the influence of visual biofeedbacks (no history of the position as for a vibrotactile biofeedback) on the Virtual Time to Contact (VTC) and distance to the boundaries of stability. Slobounov, Slobounova, et Newell (1997) describe the Virtual time to Contact (VtC). The VtC represents the "spatio-temporal proximity of the COP to the postural stability boundary". They found a decrease of the COP VTC with biofeedbacks. They found that the distance to contact was increased with both Biofeedbacks. This would suggest that while participants are further away from the stability boundaries, it does not necessarily imply that they are more stable.

**Attentional demands** Krecisz et Kuczyński (2018) and Lin et al. (2015) study the influence of a visual biofeedback and vibrotactile biofeedback respectively on COP oscillation standard deviation with a cognitive task (auditory reaction task). Both studies found an increased reaction time and reduced COP oscillations. They both concluded that using the biofeedback was attention-demanding. Krecisz et Kuczyński (2018) concluded that the biofeedback promoted a reduction of sway with a higher level of automaticity with the cognitive task (using sample entropy measures).



**Increased muscular activity and stiffness** The change in neuromuscular activity is sometimes used to assess that participants actively used the information provided by the biofeedback. Rougier (2003) studied the influence of a visual biofeedback on COG motion and neuromuscular activity (COP-COG motion). He showed that there was an increased neuromuscular activity with the use of the biofeedback. Dozza et al. (2005) explain that the reduction of sway with their biofeedback (audio biofeedback using the acceleration of the trunk on foam) the stiffness measured by the co-contraction was not increased.

## 5 Contributions

### 5.1 Brief Summary of the State of the Art

Postural control is necessary to stand upright and to orientate our body in space. Postural control is to be considered in a task-related context and dependant of the environment. The control of posture relies on the integration of sensory information necessary to generate the adapted motor commands. Theories explain that sway is minimized during quiet stance and that variability can thus be used to measure stability.

Other theories question whether sway minimization is the goal of postural control. They propose that the variability is structured and has a functional purpose. The goal of postural control would be to maintain balance while performing other tasks and not to minimize sway despite other tasks. The task-dependant modulation of sway and the fact that sway can be voluntarily reduced are in favour of a control of posture that allows and controls variability to answer the requirements of the postural and supra-postural tasks rather than reduce it.

Sensory information provided by Light Touch or Light Grip, contact of the finger or grip of a cane or stick) not providing mechanical stabilization has been studied in the literature. Sway, is modified in presence of Light Touch/Grip sensory cues, the oscillations of the body and oscillations of the COP are reduced in terms of velocity and position. The effect of Light Touch/Grip is rarely studied in the frequency domain even if the frequency content of the oscillations of body or of the COP are not-homogenous across frequencies. Different hypotheses explain the effect of Light Touch/Grip on postural control. It is assumed that Light Touch/Grip provides sensory information about the motion of the body in space. The contact is like an anchor in space, closer to the COM. This anchor while likely providing sensory information to estimate body motion and to anticipate it, constrains the movement of the body, acting like a supra-postural task. Sway is modified by supra-postural tasks may they be cognitive or motor tasks or even by volition. The

choice of the context or the instruction given to participants is thus crucial to the study of postural control. Light Touch/Grip is studied using various instructions in the literature. To our knowledge, the comparison of a voluntary minimization of sway to a relaxed stance with Light Grip has not been done. This could show that Light Grip provides sensory information that can be used to control sway.

Sensory information can be provided by external, active devices. Biofeedback devices for balance can provide sensory information about the state of the system (position, velocity...). Their influence on postural control is usually explained by a sensory-reweighing of the already existing sensory information. Vibrotactile devices have been investigated in the literature. It has been shown that the COM or COP amplitude of displacement can be decreased with a vibrotactile biofeedback. Many biofeedback devices are position-driven and are coded to bring the individual COM or COP back to a unique reference position. While many studies explain that biofeedbacks can be used to increase stability as sway is decreased, other studies high-light that the reduction if possible can be costly in terms of a higher frequency content, cognitive cost and perhaps stability is not actually increased...

## 5.2 Hypotheses

We want to study the voluntary control of sway using Light Grip and a Vibrotactile Biofeedback. We chose a minimization of sway task in an ecological bipedal stance.

Our hypothesis is twofold. First, our hypothesis is that Light Grip cues can be used to voluntary control sway in a minimization of sway task.

Our second hypothesis is that Light Grip cues can be re-weighted using a vibrotactile biofeedback to obtain a greater reduction.

We hypothesise that while the voluntary reduction of sway is possible, it might not be as efficient as the reduction observed when opening the eyes or lightly touching a fixed surface in relaxed stance as the automatic control might be hindered by the interference of volition.

## 5.3 Organisation of the Manuscript

In order to test our hypothesis, the manuscript is divided in four chapters based on the general methods used, the experiments studies followed by a conclusion.

In the second chapter, we present the general methods of our study with a brief review of metrics found in the literature and a description of common aspects of the

different experimental setups used in this thesis and metrics chosen in the time and frequency domains.

In the third chapter, the influence of Light Grip in relaxed bipedal stance is studied. In order to study the possible voluntary control of sway using Light Grip with or without a biofeedback, it is necessary to study the influence of said Light Grip in a relaxed quiet stance in absence of any instruction of voluntary control. An analysis in the time domain using RMS velocity and Ellipse Area was conducted to quantify the reduction afforded by Light Grip in quiet stance. An analysis of the Power of COP oscillations on different frequency bands showed that Light Grip reduces COP oscillations across all frequencies with a greater reduction for low frequencies. This study also showed that the COP of the hand, computed using force sensor data, and the COP of the body are correlated in the AP direction with a lead of the COP of the hand. The lag between the two signals support the idea the Light Grip provides sensory information usable for postural control.

In the fourth chapter, the influence of the Light Grip in a sway minimization task will be studied. To study the control of sway during Light Grip, the effect of the instruction to stand still compared to standing relaxed in different sensory conditions will be presented. The effect of Light Grip is compared to the effect of Vision and to both. This study shows that sway can be voluntarily reduced. Using the analysis of COP Power, we found that the reduction observed between Still and Relaxed Stance was present only for frequencies below 0.5Hz and that the reduction was greater with Light Grip for this frequency band. These findings show that Light Grip provides sensory information that can be used to reduce sway.

The fact that sway can be reduced by volition suggests that sway is not minimized in relaxed stance. The comparison of the reduction observed when we open the eyes or lightly grip a fixed handle and the one afforded by volition suggests that the voluntary control of balance might be less efficient.

In the fifth chapter, the use of a vibrotactile biofeedback provided by a handle that could be grounded to provide Light Grip cues (Grounded Grip) or free (Air Grip). Two biofeedbacks have been used. One that constrains the sway drift ( $< 0.1Hz$ ) and the other that does not constrain it. We showed that the drift, very low frequency component of COP oscillations ( $< 0.1Hz$ ) could be reduced using the biofeedbacks but with Grounded Grip only. This finding is in favour of the re-weighting hypothesis. We also showed that the biofeedback constraining the drift induced an increase of the COP high frequency content while the biofeedback which did not constrain it did not induce an increase of the COP high frequency content. We concluded that a biofeedback constraining the position around which participants swayed was less efficient and less "ecological" than

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a biofeedback not constraining the drift that gives leeway to the postural system to organize itself to answer the requirements of the task (minimization of sway task).



# Chapitre 2

## General Methods

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### Contents

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## 1 Introduction

In this thesis, we study the use of Light Grip and/or Biofeedback cues for the voluntary control of sway in non-disturbed quiet stance. The task used to evaluate the voluntary control is a voluntary minimization of sway.

## 2 Experimental Setups

### 2.1 Introduction

As previously explained, when upright, the body sways. The movement of the body is the output of postural control. It can be represented by the movement of the COM or by the movements of the different segments of the body.

Motion Capture or mocap in short can be used to capture the position of the segments of the body or joints through time using two or more calibrated cameras triangulating the 3D positions of markers. The COM can be used to describe the movement of the body in space. It can be approximated using a marker on the fifth lumbar vertebra (other methods exist ([Lafond, Duarte, & Prince, 2004](#); [Morasso, Spada, & Capra, 1999](#))).

Coordination strategies can be measured using different methods. [Zhang et al. \(2007\)](#) use, for example, the coherence between legs and trunk movements.

The body is in contact with the ground via the feet. The effect of the engaged motor commands to maintain balance are captured by the COP that reflects ankle torque.

Force Plates or Force Platforms can be used to monitor the forces and torques applied via the foot sole. One plate below each foot or one below the two feet can be used.

The Center of Pressure can be computed from the forces and moments measured by the force platform.

In the case of Light Touch or Light Grip, participants touch/grip lightly a surface/handle. The amount of applied effort needs to be monitored or recorded for further analysis. Force sensors can be used to that effect.

## 2.2 Experimental Setups

A force platform was used in the three experimental studies to obtain the Center of Pressure trajectories. Kinematics of the body (COM, shoulder, hip and ankle) were recorded in the last two studies but not in the study of Light Grip in Relaxed stance as the motion capture system could not be used for practical reasons. In all three studies, a force sensor beneath the handle was used to monitor the lightness of the Grip and/or to record data for analysis.

The [Figure 1](#) summarizes the different components of the different experimental setup used apart from specific material presented in the different chapters. The mocap system is represented while not used in the first experimental study.

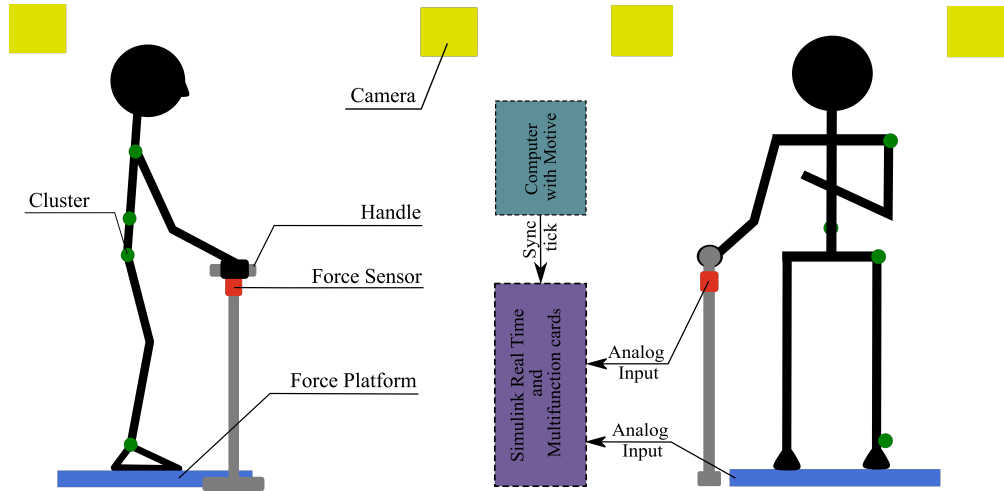


FIGURE 1: Side and Front View of the Experimental Setup

**Force Platform and Computation of the COP** The OR-6 force platform (AMTI, Watertown, MA ; Model OR-6) was used. A picture of this platform is presented in figure 2.



FIGURE 2: AMTI OR-6 Force Platform

As a single plate was used, the Center of Pressure can be computed from the forces and moments measured by the force platform using the following equation :

$$COP_{AP} = (-M_y + (F_x * h))/F_z \quad (2.1)$$

$$COP_{ML} = (M_x + (F_y * h))/F_z \quad (2.2)$$

with  $[F_x, F_y, F_z, M_x, M_y, M_z]$  the forces and moments applied by the body on the platform.  $h$  is the distance between the top of the force plate and the sensors.

**Force Sensors beneath the handle** In all experimental studies, the handle used for Light Grip was rigidly fastened on a force sensor that was grounded. The force sensor data was used to monitor the lightness of the Grip in all experimental studies but also for further analysis in the Chapter 3.



A 6-axis ATI Nano17 force sensor was used in the Chapter 3. The choice of the force sensor was motivated by the resolution needed to investigate the correlation of the forces at the hand and COP. The force sensor was replaced by an uni-axial force sensor, to measure the normal force, in the other two experimental studies as it was less constraining moment-wise and only used to check the lightness of the Grip.

A simulink Real-time computer was used to gather the data from the force platform and force sensors. NI Multifunctions cards (PCIE NI 6221 64pin and NI 6221 37pin) were used to acquire the Platform and force sensors analog inputs and synchronisation tick of the mocap system. The sampling rate used is not the same in the different chapters depending on the use ( $2kHz$  in Chapter 3,  $200Hz$  in Chapter 4 and  $4kHz$  in 5).

**Kinematics Acquisition** In the different studies (except the one presented on chapter 3 for practical reasons), the kinematics of the body (COM, shoulder, hip and ankle) were recorded using the Optitrack system. The resolution of the Optitrack system is of  $0.2mm$ . A computer with the Motive software was used to gather the data from the Optitrack cameras. The COM was approximated with a cluster positioned at the level of the fifth lumbar vertebra on the participant's back (and a bit lower in Chapter 5 for practical reasons). The other clusters (shoulder, hip and ankle joints) were positioned central to the joints. These clusters were placed on the side of the body of the non-dominant hand. The sampling rate used is  $200Hz$ .

The kinematic, force platform and force sensor data was synchronized off-line using **Matlab** Software. The software (*Motive*) used with the Optitrack system sent a synchronization tick to a NI acquisition card of the Simulink Real-time computer when the Motive recording of the trial started.

**Handles for the Light Grip** Different 3D printed handles were used for the Light Grip conditions. The handles were different depending on the requirements of each study. The handles used will be presented in the corresponding chapters including the handle used in the study in chapter 5 which is actuated.

Head-phones were used to play pink noise and for the Light Grip alarm.

**Dominant hand for the Light Touch/Grip?** In order to test the effect of Light Grip on sway, it should be decided what hand should be holding the handle. We need to decide whether to use the dominant hand or the dominant and non-dominant hand indifferently.

We decided to use the dominant hand to avoid a possible bias due to a possible difference between the two sides and as the perception sensitivity thresholds are considered lower for the dominant hand compared to the non-dominant hand (Özcan, Tulum, Pinar, & Başkurt, 2004), supposing a more effective use of sensory information.

### 3 Metrics used

We present metrics from the time and frequency domain as we only used those in our experimental studies.

#### 3.1 Brief Summary of Analyses in the Time and Frequency Domain

##### 3.1.1 Descriptive Analysis in the Time-domain

Many studies attempt to describe COP and COM profiles in the time domain in terms of displacements or velocities, either in the AP or ML direction or both directions.

A representation of a COP signal in both directions through time is shown in Figure 3A, this can be called a stabilogram. The trajectory of the COP in the AP-ML plane is shown in Figure 3B, this can be called a statokinesigram. These COP trajectories are 40s long and were recorded for a bipedal feet apart stance. The difference of amplitude is clearly visible between the two directions. A closer inspection of the evolution of the COP for the two directions reveals differences in the frequency content of the two directions ; there seems to be a higher variability in the low frequencies of the COP signal in the AP direction compared to the ML direction while high-frequency differences are less obvious.

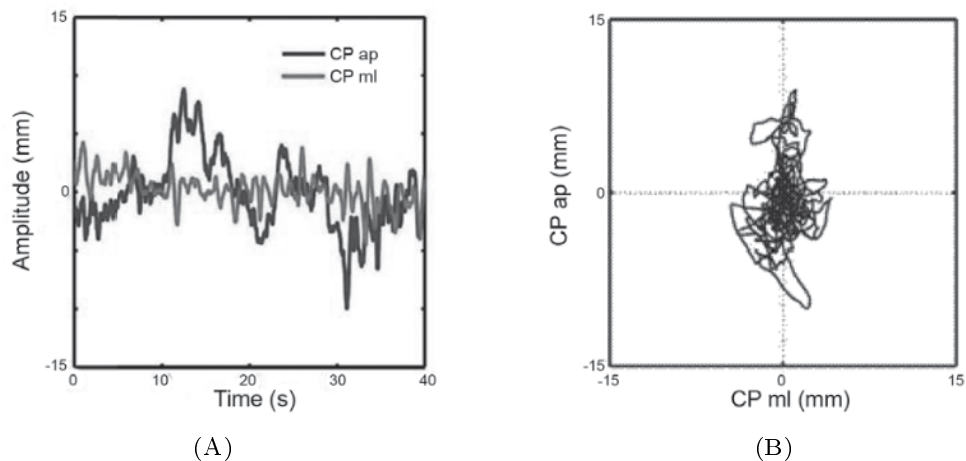


FIGURE 3: (A) Center of Pressure trajectory in the Antero-Posterior (AP) and Medio-lateral (ML) directions through time. (B) Center of Pressure trajectory in the AP-ML plane for (40s). Both plots are extracted from the review of Duarte et Freitas (2010)

As it can be seen on the Figure 3, the COP signals are highly variable in time even for quiet standing with feet apart. As previously exposed, the COM is also highly variable in time.

As hinted before, the variability across frequencies is not constant with a greater variability for low frequencies as noted by [Bensel et Dzendolet \(1968\)](#) or [Zatsiorsky et Duarte \(2000\)](#). Indeed, COM or COP time-series are bounded **non-stationary** within the bounds of the support surface for the range of time usually used for balance examination (< 90s) according to our examination and studies such as studies from [M. Riley et al. \(1999\)](#) or [Carroll et Freedman \(1993\)](#). The non-stationarity of the time-series is visible in Figure 3. This uneven/non-homogenous variability across frequencies must be considered when using time-domain measurements.

Different indexes have been used in the literature. Table 4 presents the different indexes extracted from different reviews including reviews by [Palmieri, Ingersoll, Stone, et Krause \(2002\)](#) or by [Prieto, Myklebust, Hoffmann, Lovett, et Myklebust \(1996\)](#).

Measure	Description
Mean Displacement	Average amplitude
Path	Total length of the COP (or COM) path in the AP or ML direction, and is approximated by the sum of the distances between consecutive points in the AP or ML time series
Mean Velocity	Total distance travelled by the COP (or COM) over time
RMS Displacement	Standard deviation of the displacement of the COP (or COM) around the mean
RMS Velocity	Distribution of displacements over time
Sway-Area	Area of the 95% bivariate confidence ellipse, which is expected to enclose approximately 95% of the points on the COP (or COM) path.
Peak-to-Peak Amplitude	Difference between the minimum and maximum amplitude

FIGURE 4: Table of COP and COM metrics in the time-domain extracted from [Palmieri et al. \(2002\)](#) and [Prieto et al. \(1996\)](#).

We can question whether these measurements are able to capture the structure in postural oscillations as the system is not linear and complex.

### 3.1.2 Descriptive Analysis in the Frequency Domain

**Frequency domain metrics** In the frequency domain, the amplitude of the different components can be analysed as a function of frequency.

The Power Spectral Density (PSD) can be used to quantify the variability in the frequency domain. PSD measures give an estimate of the quantity of energy in a frequency band, in other words, they give the average contribution to total power (variance) due to the components of the stochastic process between two frequencies.

The COP and COM signals are not homogeneous across frequencies, frequency analysis can help shed some light on the different postural mechanisms and possibly help capture the differences between conditions more precisely. Given that COP signals have a richer frequency content as they reflect the correcting activity and that they can be obtained more easily than COM signals, COP signals have been studied to a greater extent than COM signals in the frequency domain.

A plot of the COP displacement PSD estimate for a participant in quiet, bipedal, feet apart, stance is shown in Figure 5. This plot extracted from the review of Duarte et al (Duarte & Freitas, 2010).

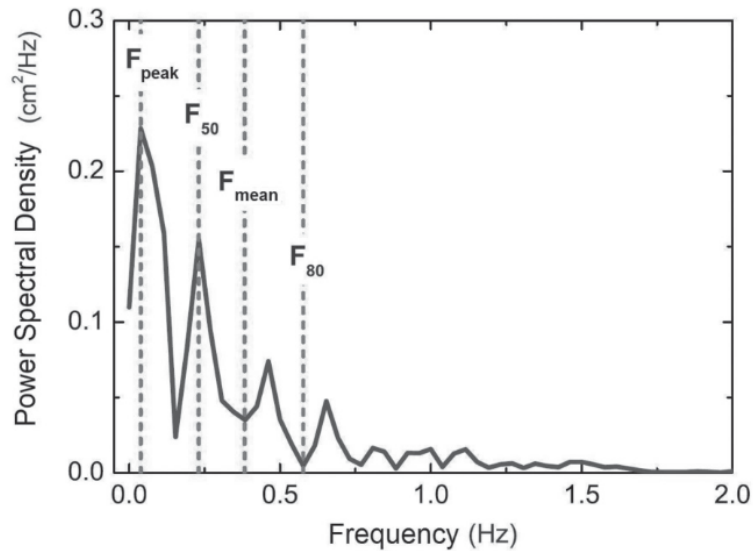


FIGURE 5: PSD plot of the COP displacement from Duarte et Freitas (2010) with the different index used

As expected by observations of time plots of COP and COM signals, plot of PSD against frequency show that the power of the signals is not distributed equally over frequency and that the power is contained in peaks at certain frequencies. (Bensel & Dzendolet, 1968 ; Zatsiorsky & Duarte, 2000).

Given the high variability for low frequencies, the duration of acquisitions must be carefully chosen. These kinds of frequency analyses require stationary signals. For the frequency content to be correctly measured, it needs to be periodically represented in the signal. The duration must be chosen accordingly but the participant's fatigue and focus must also be considered.

Different characteristics can be extracted in the frequency domain, some are reported in the Table 6.

Measure	Description
Total Power	Integrated area of the power spectrum
F50 or Median Frequency	Frequency below which 50% of the total power is found
Mean Frequency	Average Frequency
F95	Frequency below which 95% of the total power is found

FIGURE 6: Table of COP and COM metrics in the frequency-domain from [Prieto et al. \(1996\)](#)

Total Power is the area under the PSD curve, it can be calculated on different frequency bands ([Alpini et al., 2012](#) ; [Magalhães & Kohn, 2011](#) ; [Salsabili, Bahrpeyma, Esteki, Karimzadeh, & Ghomashchi, 2013](#)). This is similar to looking at the squared variability through time.

**Frequency decompositions** Results of frequency domain analysis have led researchers to decompose COP oscillations in different frequency bands to highlight postural control mechanisms.

Zatsiorsky, Duarte, Latash and colleagues in many papers ([Yamagata et al., 2016](#) ; [Zatsiorsky & Duarte, 2000](#)) explain that sway is a superposition of two processes : the migration of an equilibrium point and the oscillations around this equilibrium point. The COP signals are decomposed in two frequency bands, below and above  $0.3Hz$ , this decomposition is called rambling-trembling. Trembling ( $< 0.3Hz$ ) would reflect peripheral processes defined by the limb/body mechanics and segmental reflexes, while rambling ( $> 0.3Hz$ ) would reflect purposeful, even if not intentional, migrations of the equilibrium point. [Yamagata et al. \(2016\)](#) modified this decomposition by isolating frequencies below  $0.1Hz$  as characterizing the drift in COP oscillations.

[Baratto et al. \(2002\)](#) explain that two processes are at play for the control of posture. These processes can be observed on the COP spectrum. The COP spectrum reflects for the low frequencies the oscillations of the COM related to muscle stiffness. This a

mechanical component. It reflects for the higher frequencies, a neuromotor component. This component is considered to precede the oscillation of the COM.

We can mention the study of [Magalhães et Kohn \(2011\)](#) who studied COP oscillations for two frequency bands, one below  $0.5Hz$  and one above  $0.5Hz$ .

Researches try to find the link between frequency bands and sensory systems. The frequency bands are much discussed. [Palmieri et al. \(2002\)](#) explain that the attempts to isolate the effect of the different sensory information on specific frequency bands has not been very fruitful.

## 3.2 Metrics Used in the Different Studies Presented

### 3.2.1 Time-domain Analysis

A second order lowpass butterworth filter of  $1.5Hz$  cut-off frequency was used for the analysis in the time-domain.

Different time-domain measures were used. Only the COP was used in the Chapter on Light Grip in relaxed stance (Chapter 3) :

- RMS COP Velocity
- Area of the COP Ellipse

In the chapters on Voluntary control using Light Grip and or Biofeedback (Chapter 4 and 5), COM and body kinesmatics were studied in the time-domain :

- RMS COM Velocity
- Correlation of hip and shoulder positions

Measures of amplitude in the time-domain are highly impacted by low frequencies and non-stationarity. In this thesis, the velocity was used which renders signals stationary (at least in terms of constant mean) and the area of the ellipse was studied both with and without the drift ( $< 0.1Hz$ , greatly responsible for the non-stationarity of the signals).

Ellipse area measurements provide information on sway in the AP-ML plane and not only in one direction. Furthermore, they can be used to show difference in the orientation of sway depending on the sensory condition or type of stance. For instance, [Bryanton et al. \(2019\)](#) compared the orientation of ellipses in different sensory conditions amongst other conditions.

Palmieri in Palmieri et al. (2002) explained that displacement and velocity amplitude provide different information on postural control and are reliable when considered together.

The correlation of the hip and shoulder positions provides information on a modification of the amount of movement around the hip joint. We can thus investigate whether there is an increase of hip use.

### 3.2.2 Frequency-domain Analysis

In this thesis, we study the influence of Light Grip and/or of Biofeedbacks in the frequency domain using Power Spectral Density (PSD) estimates.

For each condition used in the different chapters, the participants performed three trials. To compare the different conditions, we concatenated the data of the trials of each participant to obtain one measure per condition per participant. For get an overall idea, PSD estimates were plotted for all participants pulled together. The data of all participants were concatenated. For each condition, one PSD estimate was obtained. This concatenation is equivalent to an average.

The data time-series are non-stationary and finite in time (80s for the Chapter 3 and 60s long for the Chapter 4 and 5). This imposes us to remove frequencies that are below  $2 * 1/totalduration(s) Hz$ . We decided to use the same frequency cut-off frequencies for all chapters. As the shortest duration is 60s, the smallest frequency we could analysis is around  $0.04Hz$ .

Given that the frequency content is not homogeneous in frequency, we decided to study the Power contained in different frequency bands.

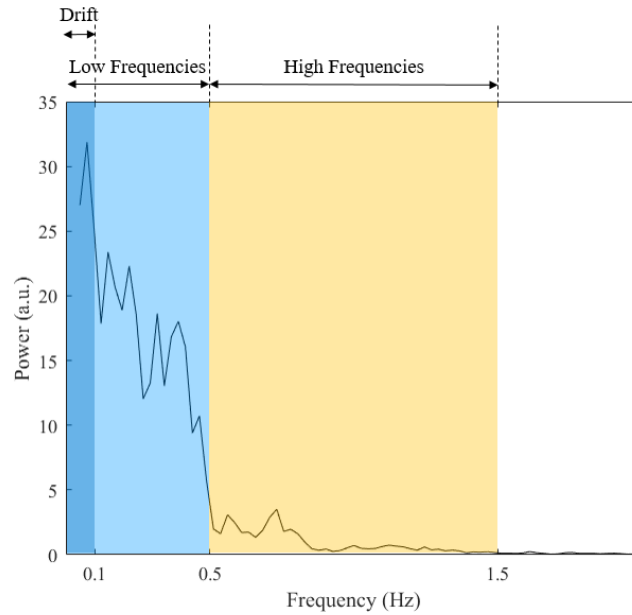


FIGURE 7: Frequency bands : trial of a participant without Light Grip in relaxed stance

As shown in Figure 7, the entire frequency range studied ( $[0.04 - 1.5Hz]$ ) was decomposed into three frequency bands :

- low frequency band ( $[0.04 - 0.5Hz]$ ),
- high frequency band ( $[0.5 - 1.5Hz]$ ),
- the drift band ( $[0.04 - 0.1Hz]$ ).

This decomposition around  $0.5Hz$  is based on the idea that COP oscillations are very similar to COM oscillations for frequency below  $0.5Hz$ . This decomposition is in line on the decomposition proposed by Baratto et al. (2002). Magalhães et Kohn (2011) use this decomposition to study Light Touch.

We used the frequency band ( $< 0.1Hz$ ) proposed by Yamagata et al. (2016) to study the drift.

## 4 Statistics

For each experiment presented, each participant performed all the conditions, three times, in a random or pseudo-random order.

For the statistical analysis in the time-domain, the measures of the three trials of each condition were averaged for each participant to obtain one measure per condition per participant.



Parametric (n-way repeated measures ANOVA) and non-parametric statistical methods (Friedman tests) using *R* software were used to determine the effect of the different factors on the different parameters extracted from the force platform, force sensor and kinematic data. The threshold for statistical significance was set to  $p = 0.05$ .

# Chapitre 3

## Light Grip in Relaxed Quiet Stance

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In this chapter, we study the influence of Light Grip on postural control in relaxed quiet stance. Light Grip similarly to light Touch likely provides sensory information related to sway that can be summarized as a stationary external reference and transient cues of sway. We will thus explore the reduction of sway variability with a focus in the frequency domain to highlight the stationary and transient informational content and effect. We will also study the correlation of COP and hand forces applied to investigate how haptic cues are related to body sway.

## 1 Introduction

Our body is swaying all the time even in quiet stance. The Center of Pressure (COP) is usually used to quantify postural control in the Anteroposterior (AP) and Mediolateral (ML) directions. COP trajectories reflect ankle torque. COP time-series, like the body oscillations, are highly variable and bounded non-stationary inside the base of support (M. A. Riley, Balasubramaniam, & Turvey, 1999; M. A. Riley & Turvey, 2002). COP oscillations and sway are affected by modifications (removal or adding) of the sensory state of the system amongst other factors. In this study, we focus on Light Grip. Sway variability is decreased in terms of amplitude or velocity in presence of Light Touch/Grip while no mechanical stabilization is possible. Light Grip like Light Touch is described as an anchor in space, providing an external stationary reference and transient cues related to sway. The contact likely provides a reference frame to detect the position and movement of the body (J. J. Jeka & Lackner, 1994). The sway-related transient cues on the skin of contact and the arm and finger/hand proprioceptive information, if congruent, are considered to allow the CNS to perceive and anticipate postural sway (Albertsen et al., 2010; Dickstein et al., 2001; Rabin et al., 2007). The mechanoreceptors embedded in the skin at the area of contact provide sensory information about the stationary external reference (Slowly Adaptive mechanoreceptors) and on the transient changes around this reference (Rapidly Adaptive and Slowly Adaptive mechanoreceptors) providing thus information about the direction, amplitude or velocity of body oscillations (Albertsen et al., 2010; Krishnamoorthy et al., 2002). In order to investigate the reduction of sway in presence of Light Touch/Grip, the correlation of the COP and tangential Force applied by the stick on the ground in the case of Light Grip (or finger for Light Touch) has been studied in the literature. Studies show that for Light Touch, the COP and touch forces in the direction of greater sway are correlated in the AP direction for bipedal stance (Clapp & Wing, 1999) and in the ML direction for tandem-romberg stance (J. J. Jeka & Lackner, 1994) with correlation coefficients between 0.4 and 0.6 and time lags around 300ms with the force leading. For Light Grip, J. J. Jeka et al. (1996) showed that the tangential force applied and the COP were correlated in the ML direction (in tandem-romberg stance) with the force leading the COP. These correlations show that the force applied is sway-related and the lag suggests that the information can be used (without any causality implication). It should be noted that a study by Rabin et al. (2007) showed that immobilizing the arm or disturbing the arm proprioception did not modify these correlations suggesting that these correlations are the result of a precision task as well as a stabilization using the information. To our knowledge, the correlation for Light Grip in bipedal stance in the AP direction has not been studied. These correlations are usually studied in the direction of the greatest instability with a touch on the side in the ML direction for the tandem-romberg stance and in front for the AP direction for bipedal

stance. Light Touch/Grip is considered to be most effective when the touch and the force changes generated are in the plane of the greatest instability (Rabin et al., 1999). These correlations have not been studied, to our knowledge, for a cane-like ecological position (neither in the AP nor ML direction) in bipedal stance, so with a contact not in the direction of the greater sway. Furthermore, the force applied by the finger or the stick in the tangential direction is used in the studies mentioned. It could be interesting and it has not been done to our knowledge to investigate the correlation of the COP of the hand and the COP of the body.

Studies have shown that COP oscillations are reduced in the time domain (displacement, velocity, area) with the Light Grip of a cane or a stick, not providing mechanical support (Albertsen et al., 2010; J. J. Jeka et al., 1996). Very low frequencies, qualified as drift ( $< 0.1Hz$ , according to Yamagata et al. (2016)) are sometimes removed before analysis (Duarte & Zatsiorsky, 2002; J. J. Jeka et al., 1996) or the analysis is performed on small time windows (of roughly 1s like in (M. Riley et al., 1999; Wulf & Mcnevin, 2002)) thus not reflecting the impact of Light Grip on very low frequencies. As presented in the state of the Art in section 3.5, very few studies to our knowledge study the influence of Light Touch or Light Grip in the frequency domain, although they usually show a decrease of power in presence of Light Touch or Grip. The COP spectrum is considered to be non-homogenous over frequencies with a greater variability for the low frequencies (Bensel & Dzendolet, 1968). A frequency analysis could provide insight on how the variability is modified over frequencies. Furthermore, a focus on the drift could reveal the impact of Light Grip on very low frequencies. As Light Grip likely provides an external stationary reference, we think that we would overlook a part of the Light Grip effect by removing the drift in COP signals before the analysis.

**Aim and Hypotheses** The aim of this study was to investigate the effect of Light Grip in relaxed quiet stance with a handle placed in an ecological position. Given that Light Grip likely provides a stationary external reference and sway-related transient cues of sway, we hypothesise in line with previous studies that sway will be reduced with Light Grip compared to without it. We expect that very slow sway (drift) will be reduced given the stationary reference provided as well as less slower sway given the transient cues provided. We expected that body sway would be correlated with haptic cues provided by the handle during Light Grip.

## 2 Methods

### 2.1 Participants

Twelve individuals (8 men and 4 women ; age =  $27.3 \pm 2.8$  years [ $M \pm SD$ ], weight =  $71.8 \pm 15.1$  kg and height =  $173.4 \pm 8.4$  cm) participated in the study. Participants were healthy and had no known neurological or muscular disorder. All participants gave informed, written consent as required by the Helsinki declaration (1964) and the local Ethics Committee. All participants were naïve to the goals of the experiment.

### 2.2 Experimental Procedure

In this study, we question the influence of Light Grip in quiet relaxed upright stance with a handle placed like a cane would be. The experiment comprised thus two experimental conditions. In both conditions, the participants were instructed to stand quietly on the platform in a relaxed manner for 90s with eyes closed. The participants' feet were parallel and apart the width of their hips.

The two experimental conditions were the following :

- **Light Grip (LG)** : The participants were lightly gripping the handle in their dominant hand at hip level. Their other arm hung loosely along the body side.
- **No Grip (NG)** : The participants had both arms hanging loosely along the body sides.

An auditory cue/alarm would inform the participants if they applied a force above the fixed threshold and that they should loosen their grip. Each condition was repeated three times in a randomized order for a total duration under 30 minutes per participant.

### 2.3 Experimental Setup

The experimental setup is presented in Figure 1A.

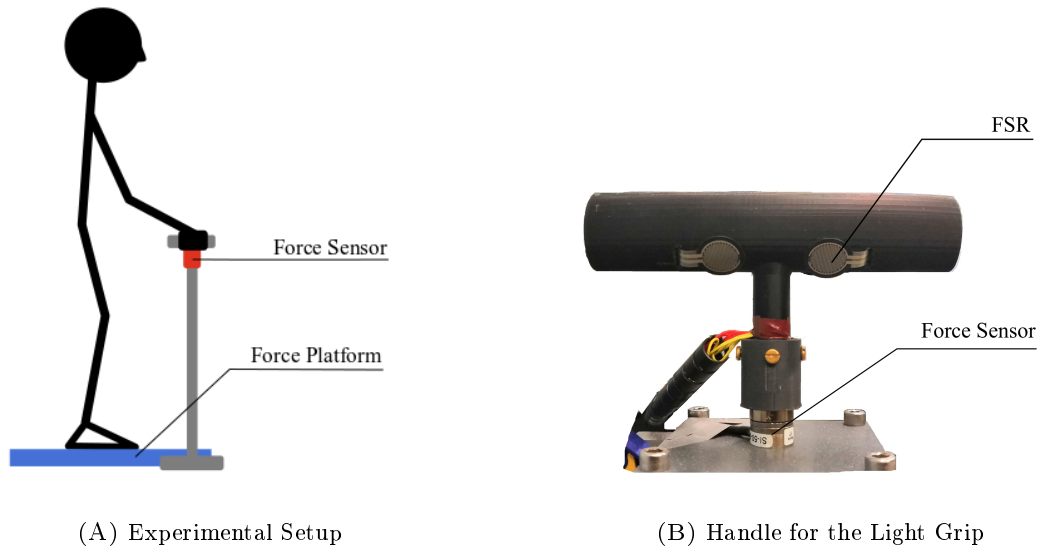


FIGURE 1: Experimental setup with a close view of the handle. The positions of the FSR on the handle surface are illustrated in the appendix A

#### 2.3.1 Data Collection for analysis

The Center of Pressure of the body ( $COP_b$ ) trajectories in the AP and ML directions were calculated using force platform data (see equation 2.2 in Chapter 2 for more details) sampled at  $2kHz$ .

The handle used for the Light Grip is tee-shaped and 3D-printed. A photo of the handle is in Figure 1B. The handle was firmly attached to the ground beside the force platform and its position and height was adjusted to ensure the participants' comfort. The handle was placed like a cane would be, an ecological position, a bit on the side and a bit forward so neither completely in the AP nor ML plane. The handle was rigidly fastened on a force sensor (ATI, Model Nano 17) to record the forces and moments applied on the handle. The force sensor signals were sampled at  $2kHz$  (same sampling rate as the force platform).  $COP_h$  is the COP of the hand on the handle, it was computed using the force sensor data.

The computation of  $COP_h$  is similar to the computation of  $COP_b$  (Equation 2.2 in Chapter 2).

### 2.3.2 Light Grip monitoring

The lightness of the Grip was monitored using the force sensor underneath the handle and five Force Sensing Resistors (FSR) mounted on the gripping surface of the handle. An auditory cue would inform the participants if they applied a force above a fixed threshold on either the force sensor or one of the FSRs. The FSRs were added to the experimental setup in addition to the force sensor already present to check if participants were not gripping the handle too firmly while applying a force on the handle below the Light Grip threshold (measured with the force sensor). The FSRs were placed in order to cover the most likely gripped surface (their positions are illustrated in the Appendix A).

If the force applied on one or several FSR sensors exceeded  $1N$  or if the normal force applied on the force sensor exceeded  $5N$  (or a moment  $> 90Nmm$ ), an alarm would inform the participants that they should loosen their grip. The normal force accepted is higher than in most studies (for the force sensor). However, participants never applied more than  $2.5N$  and [Johannsen et al. \(2007\)](#) explains that  $2.7N$  is not enough to mechanically stabilise upright stance.

The handle mounted on the force sensor with two FSR visible is shown in Figure 1B.

## 2.4 Data Processing

The experiment was designed to study Light Grip in Relaxed Quiet Stance. The Center of Pressure (COP) of the body on the ground (referred as  $COP_b$ ) was used to quantify postural control in the two conditions. The COP reflects the ankle torque ([Baratto et al., 2002](#)). We study the effect of Light Grip on COP oscillations in the time and frequency domain and investigate the temporal relationship of the oscillations of the COP of the hand with the COP of the body.

The Data Processing and Analysis was divided in two parts :

- Effect of Light Grip on COP oscillations in the time and frequency domain
- Correlation of the  $COP_b$  and  $COP_h$  displacements.

### 2.4.1 Data processing to study the Light Grip influence on $COP_b$ oscillations

**RMS  $COP_b$  Velocity** The Root Mean Square (RMS) value of the Velocity of the Center of Pressure ( $COP_b$ ) in the Antero-posterior (AP) and Medio-lateral (ML) directions

The percentage of reduction,  $r$ , of the RMS  $COP_b$  Velocity is computed as follows :

$$r = 100 * \frac{NG - LG}{NG} \quad (3.1)$$

with  $NG$  and  $LG$  the value of the RMS  $COP_b$  Velocity for the NG and LG conditions.

**$COP_b$  Power Spectral Density** COP PSD estimates were calculated for each participant and for all participants pulled together. For each participant, one PSD estimate was calculated for each condition for both the AP and ML direction. For all participants pulled together, one PSD estimate was calculated for each condition for both the AP and ML direction. The concatenation process is explained in Chapter 2. The concatenation is similar to an average.

The PSD estimates were analysed on different frequency bands. The spectrum was divided into two parts : low frequencies ( $[0.04 - 0.5Hz]$ ) and high frequencies ( $[0.5 - 1.5Hz]$ ). This decomposition is explained in Chapter 2. The frequency band  $[0.04-0.1Hz]$  corresponding to the drift was isolated to further examine the effect Light Grip on the drift. Total Power was computed for each range.

**$COP_b$  Ellipse Area and Axis** The ellipses containing 90% of the AP and ML trajectories of the COP of the body were calculated for the No Grip and Light Grip conditions. The area of the ellipses were computed as well as the axis of orientation of the ellipses. Both, area and axis of orientation, were computed using the data containing the drift or not (zero-phase shift butterworth high-pass of  $0.1Hz$  cut-off frequency).

#### 2.4.2 Data Processing to study the Cross-correlation of $COP_h$ and $COP_b$ during Light Grip

The cross-correlations were calculated for the time-series without the drift. The drift was removed for computation purposes as cross-correlation is a tool used to study stationary signals. Without the drift, the signals are more similar to a weak-stationary signal (constant mean). The COP of the hand on the handle ( $COP_h$ ) and the COP on the ground ( $COP_b$ ) in the AP and ML directions were thus band-pass filtered (zero phase-shift 1st order  $0.1 - 1.5Hz$  butterworth). The cross-correlation of the filtered and Z-normalized  $COP_h - AP$  ( $COP_h - ML$  respectively) and  $COP_b - AP$  ( $COP_b - ML$  respectively) were calculated using the MATLAB function *xcorr*.



## 2.5 Statistical Analysis

Each participant performed three trials per condition in a randomized order. For the statistical analysis in the time-domain, the measures of the three trials of each condition were averaged for each participant to obtain one measure per condition per participant. No statistical difference were found between the 3 trials for the RMS COP Velocity, COP Ellipse Area, COP Ellipse Orientation Angle, correlations coefficients and lags. Parametric and non-parametric statistical methods (*R* software) were used to determine the effect of Grip and/or Frequency Band on the different parameters extracted from the  $COP_b$  and Force applied on the handle ( $COP_h$ ). The threshold for statistical significance was set to  $p = 0.05$ .

For the analysis of the effect of 1 factor (Grip); 1-way rm ANOVA were performed if the normality hypothesis was not rejected (Shapiro-Wilk). Friedman tests were used if the residuals were not normal.

For the analysis of the effect of 2 factors (Grip x Frequency Band), 2-way (2x3) rm ANOVA were performed if the normality hypothesis was not rejected (Shapiro-Wilk). If residuals were not normal, the data was log-transformed ( $\log_{10}$ ) before performing 2-way rm ANOVA. Greenhouse-Geisser corrections were used for factors with 3 levels (Frequency band : Drift, Low frequency and High Frequency bands). Significant main effects were followed by post-hoc paired t-tests. P-values were adjusted using the Bonferroni multiple testing correction method.

### 3 Results

#### 3.1 Study of $COP_b$ oscillations in the Light Grip and No Grip conditions

The stabilograms in the AP and ML directions of a representative participant in the Light Grip (LG) and No Grip (NG) conditions are shown in Figures 2A and 2B. A visual inspection of these stabilograms reveals a reduced variability of the  $COP_b$  oscillations in the LG condition compared to the NG condition for both directions. Furthermore, the  $COP_b$  drift is less visible in the LG condition than in the NG condition for the AP direction.

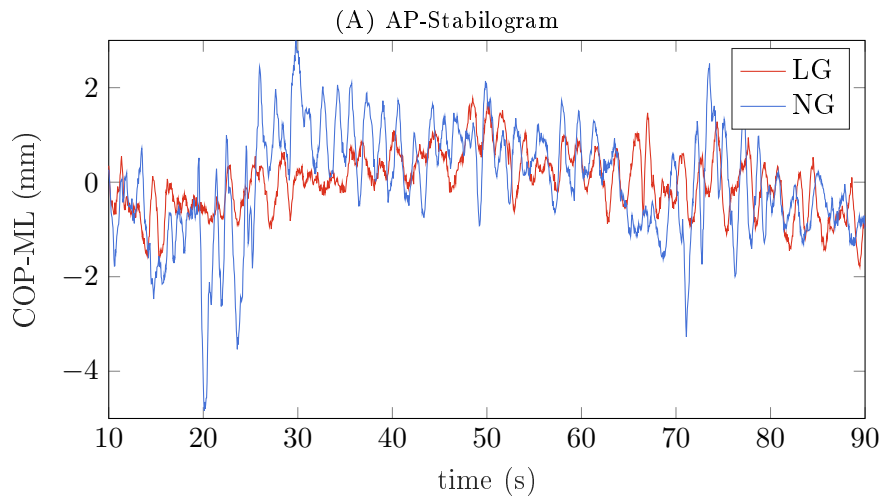
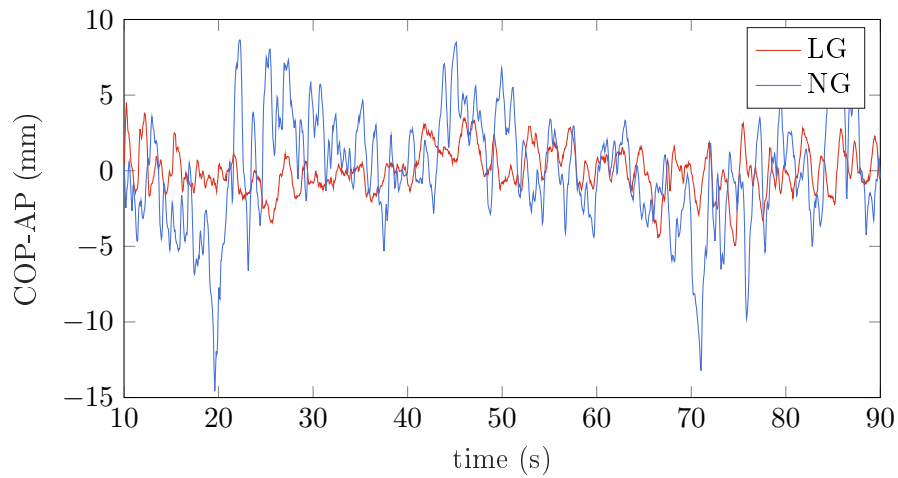


FIGURE 2: Center of Pressure ( $COP_b$ ) of a representative participant in the Light Grip (LG) and No Grip (NG) conditions in the (A) Anteroposterior (AP) and (B) Mediolateral (ML) directions.

### 3.1.1 RMS Velocity of $COP_b$ Oscillations

The mean and standard deviation of the Root Mean Square Value of the  $COP_b$  velocity in the two conditions (NG and LG) in the two directions (AP and ML) of all 12 participants are shown in the barplot in Figure 3A.

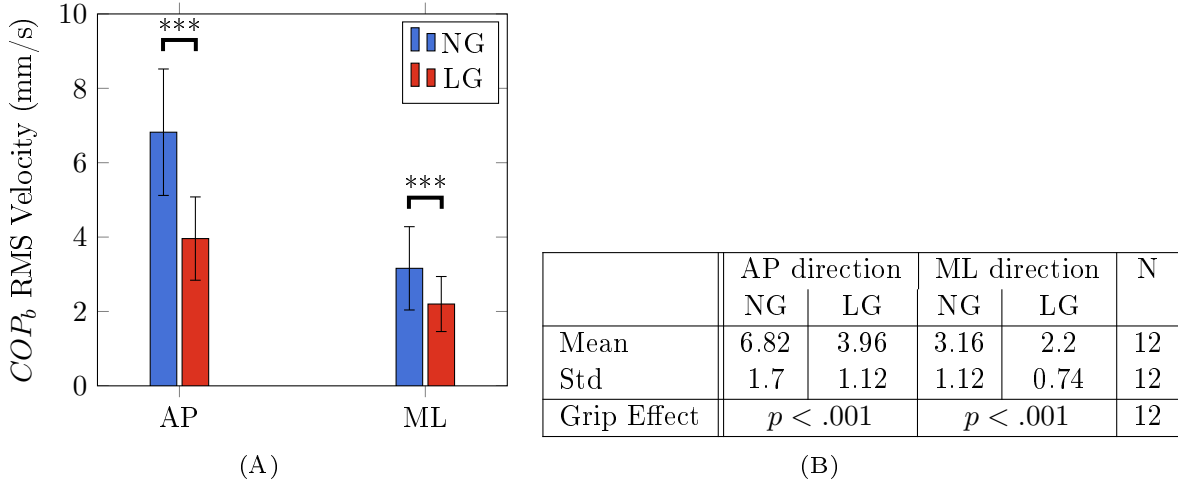


FIGURE 3: RMS Velocity of the  $COP_b$  ( $mm/s$ ) in the Antero-posterior (AP) and Medio-lateral (ML) directions for No Grip (NG) and Light Grip (LG). (A) Barplot with the significant differences between Gripping conditions; \*\*\* :  $p < 0.001$ . (B) Descriptive Statistics and P-value of the Grip effect for the two directions for N participants.

**Observations** As expected given the feet apart stance,  $RMS\ COP_b$  Velocity is greater in the AP than in the ML direction. Mean  $RMS\ COP_b$  Velocity is visibly smaller, in Figure 3A, with Light Grip in red that No Grip in blue in both directions.

**AP Direction** The one-way rm ANOVA revealed a **significant main effect of Grip** on  $RMS\ COP_b$  Velocity in the AP direction ( $F(1, 11) = 109.5, p < 0.00001$ ).

The mean percentage reduction of  $RMS\ COP$  Velocity with Light Grip compared to No Grip in the AP direction is of around  $42 \pm 7\%$ .

**ML Direction** The one-way rm ANOVA revealed a **significant main effect of Grip** on  $RMS\ COP_b$  Velocity in the ML direction ( $F(1, 11) = 20.44, p = 0.00087$ ).

The mean percentage reduction of  $RMS\ COP$  Velocity with Light Grip compared to No Grip is of around  $28 \pm 16\%$  in the ML direction.

**Summary :**  $RMS\ COP_b$  Velocity is significantly reduced with Light Grip compared to No Grip in both directions. Mean and standard deviation are reported in Table 3B.

### 3.1.2 Frequency-domain Analysis of $COP_b$ oscillations

**COP Power on the entire frequency range studied ( $[0.04 - 1.5Hz]$ )** The PSD estimates of all participants pooled together for the two conditions is presented in Figure 4A. The proportional change in power over frequencies is presented in Figure 4B. The Power over the frequency studied in the AP and ML directions for Light Grip and No Grip is shown in Figure 4C.

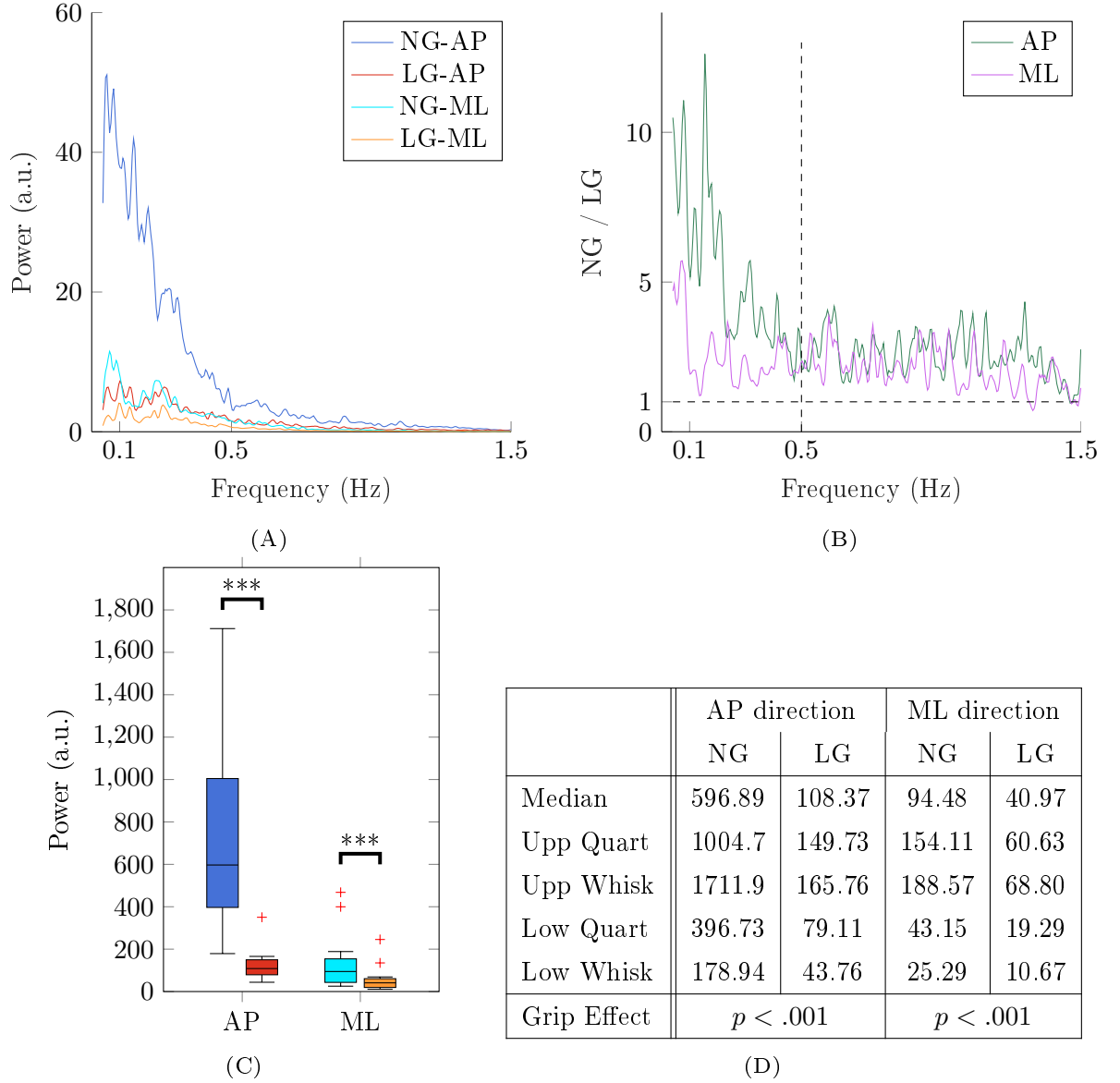


FIGURE 4: Frequency analysis on the entire frequency range ( $[0.04 - 1.5Hz]$ ) of Light Grip and No Grip in the Antero-posterior (AP) and Medio-lateral (ML) directions : (A) Plot of PSD estimates for NG and LG for all participants pooled together. (B) The proportional change in power (NG/LG). The proportional change was obtained by dividing the NG PSD by the LG PSD. (C) Boxplot of thefor the LG and NG conditions in the AP and ML directions with significant differences between LG and NG conditions indicated :  $*** = p < 0.001$ . (D) Table of the boxplot values and p-values of the effect of Grip in both directions for the 12 participants.

### Observations :

Figure 4A shows that the power contained in the  $COP_b$  signals is reduced in the Light Grip condition compared to the No Grip condition in both directions but especially in the AP direction. Furthermore, the No Grip plot in the AP direction shows greater variability for low frequencies (below  $0.5Hz$ ) than Light Grip in the two directions or No Grip in the ML direction.

The ratio slope shown in Figure 4B is very steep for frequencies lower than  $0.5Hz$  for the AP direction especially. This means that the reduction is the greatest for frequencies below  $0.5Hz$ . Around  $0.5Hz$ , the curvature changes and the slope is more flat. This change of curvature taking place around  $0.5Hz$  strengthen the frequency cut at  $0.5Hz$  between Low and High frequency bands.

The proportional change is  $> 1$  for the whole spectra meaning a reduction of COP oscillations for all frequencies in presence of Light Grip in the AP and ML directions.

Mean Light Grip COP Power shown in red (dark for AP and light for ML direction) in Figure 4C are visibly lower than Mean No Grip COP Power shown in blue in the two directions. The difference of mean is especially obvious for the AP direction.

### AP and ML directions

Friedman tests revealed that there was a **significant main effect of Grip** on COP Power in the AP direction ( $\chi^2 = 12, df = 1$  and  $p = 0.0005$ ) and in the ML direction ( $\chi^2 = 12, df = 1$  and  $p = 0.0005$ ).

### Summary :

COP Power for the entire frequency range studied is reduced with Light Grip compared to No Grip for both directions. Median, upper and lower quartile, upper and lower whiskers of the COP Power for the two conditions in the ML direction are reported in Table 4D as well as the p-values of the friedmann test on the effect of Grip.

**COP<sub>b</sub> Power, focus on specific frequency ranges** The total power was computed on the low frequency ( $[0.04 - 0.5Hz]$ ), high frequency ( $[0.5 - 1.5Hz]$ ) and drift ( $[0.04 - 0.1Hz]$ ) bands for each participant with the data of each condition pooled together to obtain on time-serie per condition per participant.

The total power for the different frequency bands is presented in Figure 5.

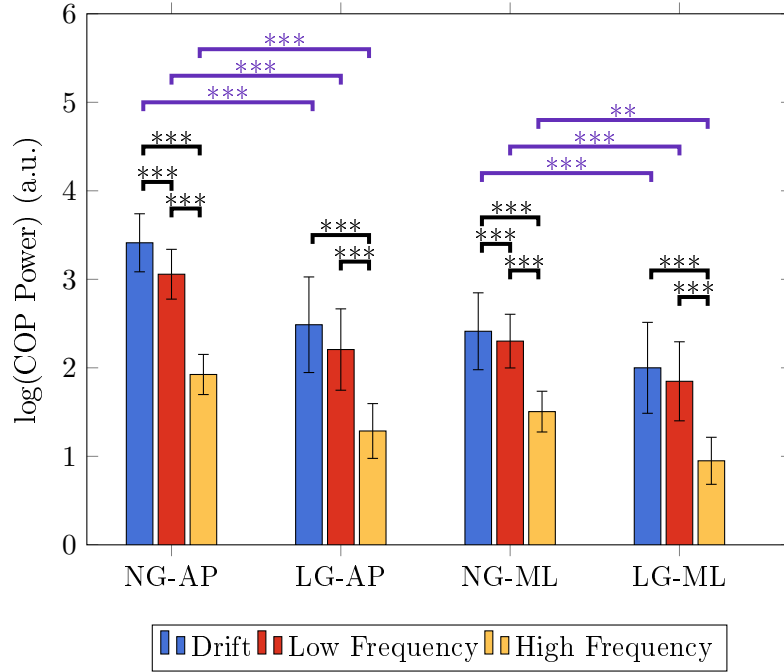


FIGURE 5: Power on the different frequency bands ( $[0.04 - 0.1Hz]$  for the drift,  $[0.04 - 0.5Hz]$  for the low frequencies and  $[0.5 - 1.5Hz]$  for the high frequencies) for the Light Grip (LG) and No Grip (NG) conditions in the Antero-posterior (AP) and in the Medio-lateral (ML) directions. Differences between frequency ranges are indicated in black and differences between Grip conditions in purple.  $** = p < 0.01$ ,  $*** = p < 0.001$

#### AP direction

A two-way rm ANOVA was performed to evaluate the effect of Grip over frequency bands on COP Power in the AP direction. The analysis revealed a **main effect of Grip and Frequency band and an interaction of Grip and Frequency band**. Results of pairwise comparisons and descriptive statistics (mean and standard deviation) are summarized in Tables 1 and 2. The statistical analysis is detailed in appendix A.

*Summary* : For all frequency bands, COP Power is reduced with Light Grip compared to No Grip (**LG < NG**) but the effect of Grip is greater for the drift and low frequency bands than the high frequency band. This is consistent with the less steep slope of the reduction for frequencies above  $0.5Hz$  on the Figure 4B. The difference between frequency bands was greater for No Grip than Light Grip (interaction Grip x Frequency bands). For No Grip, all frequency bands were significantly different (**NG : Drift  $\neq$  Low Freq**

$\neq$  **High Freq**). For Light Grip, the low frequency and Drift band were different from the high frequency band while the drift and low frequency bands were not different (**LG : Drift  $\neq$  High Freq and Low Freq  $\neq$  High Freq but Drift  $\approx$  Low Freq**).

### ML direction

A two-way rm ANOVA was performed to evaluate the effect of Grip over Frequency Bands on COP Power in the ML direction. The analysis revealed a **main effect of Grip and Frequency band** but no interaction. Results of pairwise comparisons and descriptive statistics are summarized in Tables 1 and 2. The statistical analysis is detailed in appendix A.

*Summary* : For all frequency bands, COP Power is reduced with Light Grip compared to No Grip (**LG < NG**). For No Grip, all frequency bands were significantly different (**NG : Drift  $\neq$  Low Freq  $\neq$  High Freq**). For Light Grip, the low frequency and Drift band were different from the high frequency band while the drift and low frequency bands were not different (**LG : Drift  $\neq$  High Freq and Low Freq  $\neq$  High Freq but Drift  $\approx$  Low Freq**).

	AP direction		ML direction		N
	NG	LG	NG	LG	
Drift	3.41 $\pm$ 0.33	2.49 $\pm$ 0.54	2.41 $\pm$ 0.43	2.0 $\pm$ 0.51	12
Low Frequency	3.06 $\pm$ 0.28	2.21 $\pm$ 0.46	2.30 $\pm$ 0.30	1.85 $\pm$ 0.45	12
High Frequency	1.92 $\pm$ 0.23	1.29 $\pm$ 0.31	1.51 $\pm$ 0.23	0.95 $\pm$ 0.27	12

TABLE 1: Descriptive statistics (Mean  $\pm$  Standard Deviation) of the COP Power on the 3 frequency range studied for N participants.

	Pairs	AP direction	ML direction
Grip	NG-drift vs LG-drift	<b><math>p &lt; .001</math></b> $\searrow$	<b><math>p &lt; .001</math></b> $\searrow$
	NG-low freq vs LG-low freq	<b><math>p &lt; .001</math></b> $\searrow$	<b><math>p &lt; .001</math></b> $\searrow$
	NG-high freq vs LG-high freq	<b><math>p &lt; .001</math></b> $\searrow$	<b><math>p = .001</math></b> $\searrow$
Freq band	NG-drift vs NG-low freq	<b><math>p &lt; .001</math></b> $\searrow$	<b><math>p &lt; .001</math></b> $\searrow$
	NG-drift vs NG-high freq	<b><math>p &lt; .001</math></b> $\searrow$	<b><math>p &lt; .001</math></b> $\searrow$
	NG-low freq vs NG-high freq	<b><math>p &lt; .001</math></b> $\searrow$	<b><math>p &lt; .001</math></b> $\searrow$
	LG-drift vs LG-low freq	$p = 0.099$	$p = 0.065$
	LG-drift vs LG-high freq	<b><math>p &lt; .001</math></b> $\searrow$	<b><math>p &lt; .001</math></b> $\searrow$
	LG-low freq vs LG-high freq	<b><math>p &lt; .001</math></b> $\searrow$	<b><math>p &lt; .001</math></b> $\searrow$

TABLE 2: P-values of the post-hoc t-test pairwise comparisons for the two Grip levels and for the three frequency bands in the AP and ML directions. Significant differences are in bold. **Arrows indicate the direction of the change between the first and second part of the pair.**

3.1.3  $COP_b$  Ellipses

The  $COP_b$  ellipses area and orientation for Light Grip and No Grip conditions were analysed with and without the drift.

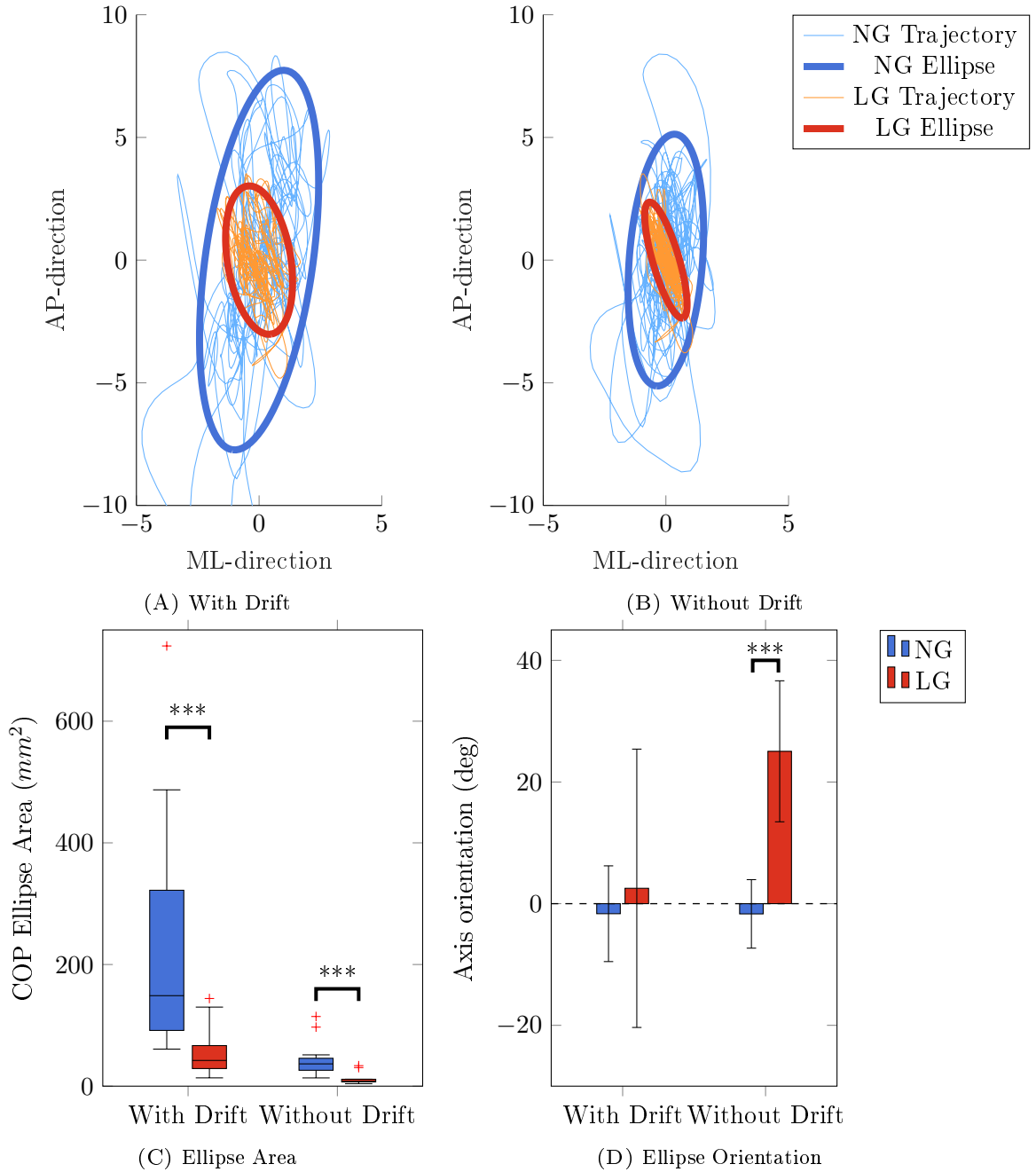


FIGURE 6: (A) and (B) represent  $COP_b$  trajectory for the No Grip (NG) and Light Grip (LG) conditions and Ellipse associated, with and without the drift respectively. These are representative trials of one participant. (C) Boxplot of the  $COP_b$  ellipse Area and (D) Orientation of the ellipses for the the No Grip (NG) and Light Grip (LG) conditions for all participants pooled together with and without the drift, respectively.

\*\*\* :  $p < 0.001$



**Analysis of the  $COP_b$  Ellipse Area** The Analysis was performed with and without the drift. The difference in area is clearly visible on the boxplots in Figure 6C with and without the drift as well as on the plots of the trajectories and ellipses of a representative participant in Figures 6A and 6B. The ellipse area seems a lot smaller without the drift than with it for both conditions.

Friedman tests reveal a **significant effect of Grip** on the area of the COP ellipse **with the drift** ( $\chi^2 = 12, df = 1, p = 0.0005$ ) and **without the drift** ( $\chi^2 = 12, df = 1, p = 0.0005$ ).

Summary : The Area is significantly reduced with Light Grip compared to No Grip with and without the Drift (**LG** < **NG**). Results of the analysis and descriptive statistics (median and interquartile ranges) are summarized in Table 7A.

**Orientation of the ellipses** The difference of orientation of the axes of the No Grip and Light Grip ellipses was analysed. The Figure 6D shows the main orientation of sway in the two conditions with and without the drift. An angle of  $0^\circ$  represents an oscillation in the AP direction. The difference of orientation of the NG and LG ellipses is clearly visible in Figure 6B but less in the Figure 6A.

The analysis of the orientation angle of the ellipses reveals a **significant effect of Grip without the drift** ( $F(1, 11) = 41.2, p < 0.0001$ , 1-way rm ANOVA) but no significant effect with the drift ( $F(1, 11) = 0.283, p = 0.605$ , 1-way rm ANOVA).

Summary : The orientation of sway with Light Grip without drift is shifted compared to No Grip (**Without Drift : Axis NG**  $\neq$  **LG**). Participants sway toward the handle as they sway backwards with Light Grip while they sway in the AP direction without Grip. Results of the analysis and descriptive statistics (mean and standard deviation) are summarized in Table 7B.

	With drift		Without drift	
	NG	LG	NG	LG
Median ( $mm^2$ )	148.76	42.26	35.63	8.06
Upp Quart	322.07	66.69	45.84	11.34
Upp Whisk	487.12	129.97	51.45	11.39
Low Quart	91.62	28.93	26.11	7.00
Low Whisk	60.91	13.65	13.57	4.02
Grip Effect	$p < .001$		$p < .001$	

(A) Ellipse Area

	With drift		Without drift	
	NG	LG	NG	LG
Mean ( $deg$ )	-1.65	2.53	-1.68	25
std	7.87	22.88	5.63	11.59
Effect	$p = .6$		$p < .001$	

(B) Ellipse Orientation

FIGURE 7: Descriptive statistics and p-values of the effect of Grip for (A) Area of the COP Ellipse and (B) orientation angle with or without the drift for 12 participants.

### 3.2 Study of the Correlation between the Body COP ( $COP_b$ ) Displacements and the Hand COP ( $COP_h$ )

Cross-correlation functions were calculated to investigate the temporal relationship between the body COP ( $COP_b$ ) on the ground and the hand COP ( $COP_h$ ) on the handle. The cross-correlations were calculated in the AP and ML directions.

For AP correlations, one participant showed a time-lag peak above 1s for one trial. This participant was excluded from further analysis. For ML correlations, eight participants showed a peak above 1s. The ML correlations were not further analysed.

The correlation coefficients and time lags calculated in the AP direction are shown in Figure 8. A plot of 30s of a representative trial is shown in Figure 8A clearly showing the correlation of the two signals.

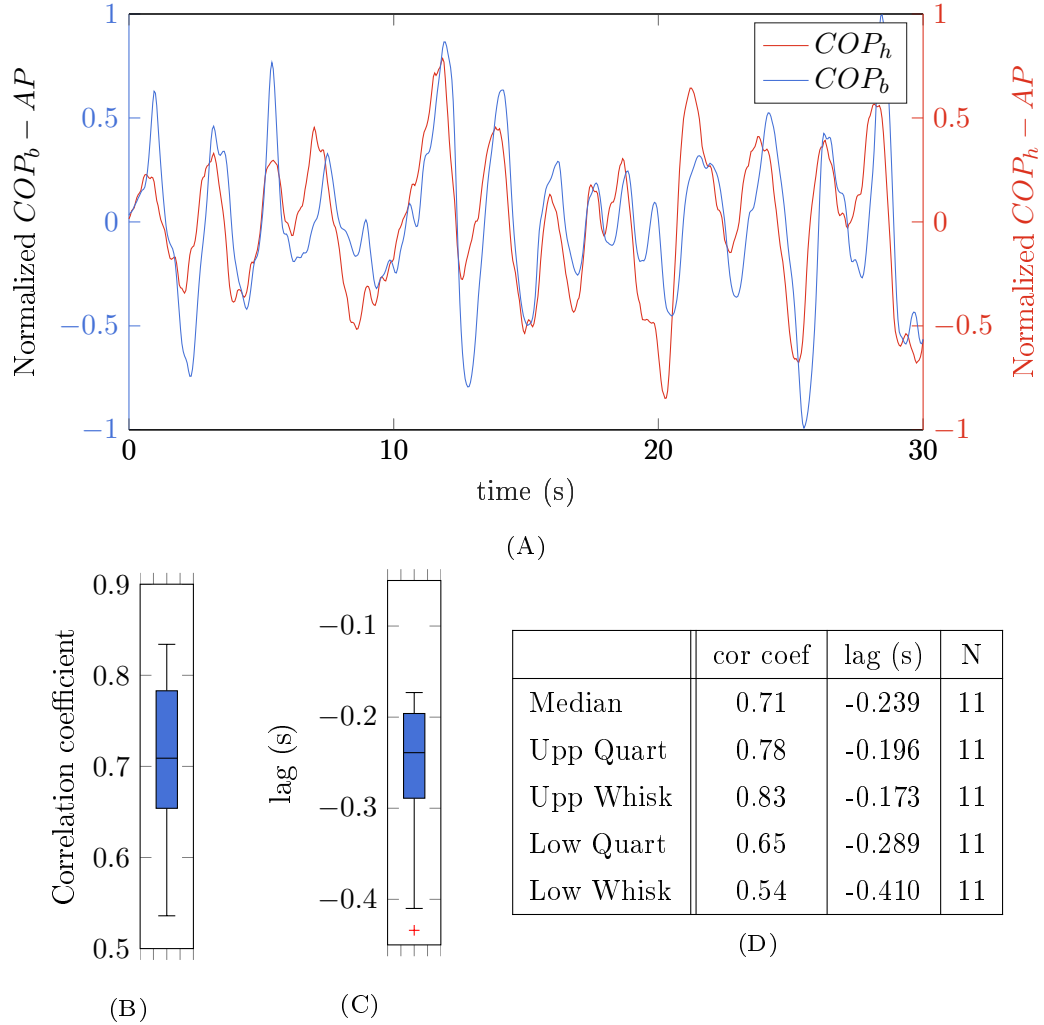


FIGURE 8: (A) Normalized  $COP_b$  and  $COP_h$  signals in the Antero-posterior (AP) direction of a representative participant for 30s (correlation coefficient and time lag roughly equal to the median of the group). Boxplot of the (B) correlation coefficient and (C) time lag in the AP direction with the boxplot values in (D).

The correlation coefficients in the AP direction are significantly different than 0 ( $p < 0.001$ , t-test). In the AP direction, the median time lag is roughly  $-0.24s$ , this means that change in the  $COP_h - AP$  occurred prior to the changes in  $COP_b - AP$  displacements.

The orientation axes of the ellipses of the COP of the body and COP of the hand applied to the handle are not collinear. The study is presented in Appendix A.

## 4 Discussion

We studied the influence of Light Grip on postural control on young and healthy individuals. 12 Participants stood relaxed, eyes closed while lightly gripping a handle fixed in space or without gripping anything. The allowed amount of force applied on the handle ensured that the Grip was not providing any mechanical support as in previous numerous studies (Albertsen et al., 2010 ; J. J. Jeka et al., 1996 ; Sozzi et al., 2018).

This influence was first assessed using COP based metrics in the time and frequency domains. Secondly, we studied the temporal relationships of the haptics cues and displacement of the body.

In short, we found that :

- the RMS COP Velocity was reduced with Light Grip compared to No Grip in both the AP and ML directions.
- the Area of the COP Ellipse was reduced with Light Grip compared to No Grip with the Drift and without the Drift. The orientation of the ellipse was shifted with Light Grip without the drift.
- The COP Power was reduced with Light Grip compared to No Grip for the entire frequency range in both directions. The Power was reduced to a greater extent for the low frequency ( $< 0.5Hz$ ) and Drift ( $< 0.1Hz$ ) bands than high frequency ( $0.5 > f > 1.5Hz$ ) in both directions.
- The COP of the hand and COP of the body are positively correlated with the COP of the hand leading.

## 4.1 Sway-related Cues

### 4.1.1 Interplay of the COP of the hand and COP of the body

The correlation of the COP of the hand and the COP of the body was computed. We choose to use the COP of the hand instead of the tangential forces like in previous studies (Clapp & Wing, 1999; J. J. Jeka et al., 1996; J. J. Jeka & Lackner, 1994). The results are, as expected, similar to those obtained in studies using directly the tangential forces. This study shows that  $COP_b$  oscillations and  $COP_h$  oscillations are correlated in the AP direction with a median lag of 240ms with the  $COP_h$  leading the  $COP_b$  signal. This result is in line with findings from Clapp et Wing (1999).

This correlation shows that haptic cues provided by the contact are sway-related. As the movements of the COP of the hand is leading, it is possible that haptic cues are used to anticipate the movements of the body. This correlation does not give us any information on the goal of postural control nor on the use of these information. These sway-related cues might be used to reduce sway if the goal of postural control is to minimize sway or to reduce sway to facilitate the grip.

### 4.1.2 Effect of Light Grip on $COP_b$ Oscillations

A significant decrease of  $COP_b$  oscillations, assessed by COP-based measures in the time and frequency domains was observed with Light Grip compared to No Grip.

In terms of velocity, regarded as a reliable index, we found that  $COP_b$  RMS Velocity is significantly smaller with Light Grip than with No Grip. This reduction was observed both in the AP and ML directions with a percentage reduction of 42% and 28% respectively. The reduction of the velocity of  $COP_b$  oscillations support the idea that Light Grip provides information about the velocity of the body and not only its position.

In terms of amplitude of displacements in the AP-ML plane, we found that the area of  $COP_b$  Trajectory ellipse is also significantly smaller with Light Grip than No Grip. As  $COP_b$  time-series are non-stationary,  $COP_b$  displacement measures are greatly influenced by the drift contained in the time-series. While representing the entirety of the data, they might not reflect well the higher frequencies of sway. With this consideration in mind, the Area of  $COP_b$  trajectories were also studied without the drift contained in the data. Ellipse Areas for Light Grip and No Grip conditions are still significantly different without the drift showing that  $COP_b$  displacements in the AP-ML plane are reduced with Light Grip and that this reduction cannot be explained by the reduction of the drift contained in the data and most present for No Grip trials. The difference in

size of the areas with and without the drift is quite striking (149 vs  $36\text{mm}^2$  for No Grip). Duarte et Zatsiorsky (2002) explain that the area of the ellipse can be divided by 2 if frequencies below  $0.05\text{Hz}$  are removed.

These results are in line with previous studies on Light Touch and Light Grip showing a decrease of  $COP_b$  variability may it be  $COP_b$  displacement (Albertsen et al., 2010 ; J. J. Jeka et al., 1996 ; Sozzi et al., 2018)) or  $COP_b$  velocity (J. J. Jeka & Lackner, 1994 ; Krishnamoorthy et al., 2002 ; Mauerberg-Decastro et al., 2014), we found that  $COP_b$  variability was reduced in the time-domain with Light Grip compared to the No Grip condition.

A frequency analysis of  $COP$  oscillations shows that the Power of  $COP$  displacements is smaller for Light Grip than No Grip. The power over frequencies is not constant for No Grip and Light Grip. The observed PSD for No Grip are in line with other studies (Bensel & Dzendolet, 1968). The evolution of the power through frequencies is similar to those observed by Magalhães et Kohn (2011) or J. R. Lackner et al. (2000). The power over frequency varies differently between Light Grip and No Grip conditions. The study of power on different frequency bands shows that the frequency content is different between frequencies above and below  $0.5\text{Hz}$ . The power is mostly reduced for frequencies below  $0.5\text{Hz}$  and for the drift, this can be also observed on the change of curvature around  $0.5\text{Hz}$  on the plot of the power of NG over LG shown in Figure 4B. The reduction of the drift and of low frequencies supports the idea that Light Grip is providing information of an external stationary reference ("position information"). The reduction of the drift and of the rest of the frequency content as well is consistent with the characteristics of the Slowly Adaptive and Rapidly Adaptive mechanoreceptors that can be used to detect very slow and "rapid" changes of the body motion when integrated with proprioceptive information of the arm and body. The decrease of higher frequencies ( $> 0.5\text{Hz}$ ) supports the idea that postural control is not degraded by the contact task but that the overall amount of correcting activity is reduced and not only in part.

These modifications both in terms of velocity and position are in line with other studies (Albertsen et al., 2010 ; J. Jeka et al., 1998 ; J. J. Jeka, Schöner, Dijkstra, Ribeiro, & Lackner, 1997 ; Krishnamoorthy et al., 2002) showing that Light Touch/Grip provides a anchor point, an external stationary reference and transient cues of sway (velocity-like information) integrated with proprioceptive cues.

We think that our study highlights the usefulness of frequency domain study of Light Grip (and Light Touch) as it shows how Light Grip affects the different frequencies with a greater impact for the low frequencies.

## 4.2 An Ecological Position

Rabin et al. (1999) explain that the effect of Light Touch is greater if it is in the greater instability direction. However, in this experiment, we used a position that was chosen to be ecological. The handle was on the side of the participant at hip height but a bit anterior to the body. The handle was thus not directly in the AP nor ML plane. Sway is known to be predominant in the AP direction for bipedal feet apart stance. The AP and ML directions were not directly compared. The hypothesis that AP and ML control are independent can be questioned in our case as the position of the handle creates an asymmetry. The mean reduction of the velocity was higher in the AP direction than in the ML direction and the plot showing the reduction in the frequency domain shows clearly a greater reduction in the AP direction. The analysis of the correlation of the COP of the hand and COP of the body was only conclusive for the AP direction. This is in line with a study from J. J. Jeka et al. (1996). They compared two touches and found that the one with the correlation with the force leading provided the greater reduction. Interestingly, we observed a shift in the direction of  $COP_b$  oscillations for No Grip and Light Grip (orientation axes of the ellipses). This shift was only observed without Drift. The sway in the No Grip trials was mostly in the AP direction meanwhile in the Light Grip trials, participants swayed a little away from the handle when leaning forward and closer to the handle when leaning backwards. An investigation of mechanical links while gripping a handle would perhaps shed some light on the implications of this result. Dickstein, Peterka, et Horak (2003) showed that participants swayed toward the touch, they explain this by the anticipation that touch cues could be useful for the stabilization of the body. We can hypothesise, in line with Dickstein et al. (2003) that perhaps, participants swayed toward the handle when going backward as the stability margin is smaller in the posterior direction.

## 5 Conclusion

The body COP variability was reduced in the time and frequency domain with Light Grip. Furthermore, the body COP displacements are correlated with the hand COP with the COP of the hand leading. These results support the hypothesis that Light Grip provides sway-related information about the position of contact but also about the movement around the position of contact. We think that it could be interesting to study separately the spatio-temporal information (external reference) and transient cues of sway using frequency analysis. We think that this study highlights the usefulness of frequency analysis to study Light Grip. This study of the effect of Light Grip in the

frequency domain with the instruction to relaxed stance can be a base-line to study the voluntary control of sway using Light Grip.

## Chapitre 4

# Is Voluntary Control of Sway using Light Grip Possible ?

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## 1 Introduction

Postural control depends of the sensory information available, of the task at hand and the context. Studies show that sway is reduced with Light Grip and/or Vision (Albertsen et al., 2010 ; Backlund Wasling et al., 2005 ; Paulus, Straube, & Brandt, 1984 ; Sozzi, Do, Monti, & Schieppati, 2012). As shown in the previous study (Chapter 3), the variability of the COP position is reduced in the frequency domain for all frequencies between 0.04 and 1.5Hz and thus including the drift ( $< 0.1Hz$ ) likely thanks to the stationary external reference provided by the Light Grip and possibly to the positional constraint added by the gripping task. Visual cues are possibly not providing very low frequency information compared to Light Touch/Grip (Backlund Wasling et al., 2005 ; J. Jeka et al., 1998). Many studies have shown that postural sway can be modified by the addition of a task (dos Santos et al., 2019 ; Lee et al., 2019). For example, theories explain that sway may be modulated to facilitate supra-postural tasks. The reduction of sway observed with Light Touch or Vision is sometimes explained by the addition of a supra-postural task. Looking or touching would add a constraint on postural sway that would be reduced to facilitate touch or vision. T. Stoffregen et Pagulayan (2000) for Vision or M. Riley et al. (1999) for Light Touch explained that postural control facilitate vision and touch by reducing sway. Furthermore, postural sway is modulated in the presence of a concurrent cognitive task (Pellecchia, 2003 ; Richer, Saunders, Polskaia, & Lajoie, 2017). The task-depend modulation of sway shows that postural control is cognitively penetrable. Moreover, it appears that the focus of attention on the postural task impacts postural control (Mcnevin & Wulf, 2002 ; Remaud, Boyas, Lajoie, & Bilodeau, 2013 ; Vuillerme & Nafati, 2007). Vuillerme et Nafati (2007) and McNevin, Shea, et Wulf (2003) amongst other found that attentional focus on body sway can be detrimental to postural control. The focus of attention on body sway is referred as an internal focus. It promotes a less automatic and less efficient control than an external focus. An external focus refers to a displacement of the focus of attention to the consequence of the action. The supra-postural task of lightly gripping instead of only gripping the handle might be associated to an external focus of attention (Mcnevin & Wulf, 2002) Several studies have shown that sway can be modified by volition. Sway can be voluntarily reduced. These studies compare the amount of sway in relaxed stance and the amount of sway with the instruction to minimize sway (R. C. Fitzpatrick et al., 1992 ; Loram et al., 2001 ; Reynolds, 2010 ; Ueta, Okada, Nakano, Osumi, & Morioka, 2015 ; Zok et al., 2008). The instruction to minimize sway is likely associated to an internal focus of attention. The possible reduction shows a part of sway can be voluntarily reduced and thus that it is not minimized in relaxed stance. Part of these studies perform this comparison with and without vision (R. C. Fitzpatrick et al., 1992 ; Loram et al., 2001 ; Reynolds, 2010). They show that while the reduction is possible

with Eyes Closed or Eyes Open, visual cues allow a greater reduction. This shows that the effect of vision cannot be summarized as a supra-postural task.

The effect of Light Touch/Grip are studied with various instructions, sometimes participants are asked to stand still (Albertsen et al., 2010; Clapp & Wing, 1999; Magalhães & Kohn, 2011; Vuillerme, Isableu, & Nougier, 2006), sometimes to stand relaxed (J. Misiaszek et al., 2016; M. A. Riley et al., 1999; Silva, Magalhães, & Kohn, 2019) and sometimes they are asked to sway as little as possible while being relaxed (Johannsen et al. (2014), Caudron et al. (2010)...) and unfortunately, the instruction is sometimes not specified in the reported experimental protocol (J. J. Jeka et al., 1997; Krishnamoorthy et al., 2002; J. Lackner et al., 2003; Sozzi et al., 2018). By comparing sway in relaxed stance with sway with the instruction to minimize with Light Grip, we can highlight that Light Grip provides sensory information that can be used to control sway. We can thus show that Light Grip cannot be summarized as a supra-postural task that possibly does not provide sensory information.

**Aim and hypotheses of this study** In this study, we investigate the effect of the instruction to minimize sway (still stance) compared to standing relaxed in different sensory contexts (Light Grip and/or Vision).

Our primary hypothesis is that Light Grip cues can be used to voluntarily reduce sway as it provides an external stationary reference closer to the COM (Franzén et al., 2011)) and cues about the movement of the body ((Albertsen et al., 2010; Backlund Wasling et al., 2005; Krishnamoorthy et al., 2002). Furthermore, the supra-postural task of lightly gripping and not just gripping the handle may be associated with an external focus of attention promoting a more efficient and automatic control (Mcnevin & Wulf, 2002). We can also hypothesise that the very slow sway (drift) will be reduced with the instruction to minimize for Light Grip but not with Vision and not to the same extent as Light Grip.

## 2 Methods

### 2.1 Participants

13 people (8 men and 5 women ; age =  $25.7 \pm 2.5$  years [ $M \pm SD$ ], 10 right-handed and 3 left handed) participated in the study. All participants were healthy and had no known neurological or muscular disorder. Participants gave informed, written consent as required by the Helsinki declaration (1964) and the local Ethics Committee. All participants were naïve to the goals of the experiment.

### 2.2 Procedures

The experiment was designed to study a sway-minimization task in the presence or absence of two sensory modalities : Light Grip and Vision.

#### 2.2.1 Experimental Conditions

Participants stood upright, bare foot, either relaxed or actively reducing their sway/actively staying still for 1-minute trials. The participants' feet were parallel and apart the width of their hips. Participants were either Eyes Closed or Eyes Open. Participants held lightly a handle in their dominant hand or not. The eight conditions are the following :

- Relaxed quiet standing, No Grip and Eyes Closed (R-NG-EC)
- Relaxed quiet standing, Light Grip and Eyes Closed (R-LG-EC)
- Relaxed quiet standing, No Grip and Eyes Open (R-NG-EO)
- Relaxed quiet standing, Light Grip and Eyes Open (R-LG-EO)
- Still quiet standing, No Grip and Eyes Closed (S-NG-EC)
- Still quiet standing, Light Grip and Eyes Closed (S-LG-EC)
- Still quiet standing, No Grip and Eyes Open (S-NG-EO)
- Still quiet standing, Light Grip and Eyes Open (S-LG-EO)

As for instructions : for the Relaxed conditions, we asked participants to stay completely relaxed and to let their thoughts wander. For the Still conditions, we asked participants to try as hard as they could to reduce the movement of their body. These are the same instructions as [Reynolds \(2010\)](#) and [Ueta et al. \(2015\)](#).

For the Eyes Open conditions, participants could focus on a point on the wall, 1.6m away in a structured environment.

For the Light Grip conditions, participants held a handle rigidly fixed to the ground at hip level with their dominant hand. An auditory cue would warn the participant if they applied a force on the handle exceeding  $1N$ . The participants were instructed to loosen their grip upon hearing the auditory cue.

### 2.2.2 Experiment Flow

The participants were first explained how the experiment would unfold. The eight conditions (2 Instructions x 2 Grip x 2 Vision) were randomly repeated three times amounting to a total of 24 trials for a total duration of an hour and a half. Participants were reminded to stand relaxed or Still before each trial. A discussion with the participants took place after the trials. Each participant was asked to explain what they perceived and experienced before any specific questions to limit bias in answers. After the discussion, participants were asked to answer specific questions. These questions were related to the amount of focus required to minimize sway or to maintain a Light Grip; whether they believed they had stiffened to minimize sway; whether they believed they had been able to reduce and in which sensory conditions; whether they believed that they knew in what direction and with what amplitude they swayed. Their answers were used to discuss the results and to orient further studies.

### 2.3 Apparatus

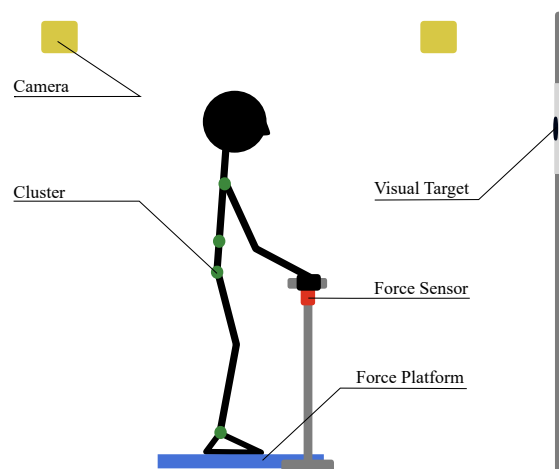


FIGURE 1: Experimental Setup

The experimental setup is presented in figure 1.

Kinematics of the body (COM, shoulder, hip and ankle) were recorded. COP trajectories in the AP direction were calculated.

The handle used for the Light Grip was 3D-printed. The handle was rigidly fastened on a uniaxial force sensor to record the normal force applied on the handle. The handle was firmly attached to the ground beside the force platform and its position was adjusted to ensure participants' comfort. The force sensor was used to monitor the grip of the participant.

The signals from the OptiTrack system, force platform and force sensor were sampled at  $200Hz$ .

## 2.4 Data Processing

As explained previously, the experiment was designed to study a sway-minimization task in the presence or absence of two sensory modalities : Light Grip and Vision.

Different scores were computed to study the effect of the sway-minimization task and the effect of the sensory context.

Signals, once synchronized, were processed off-line with MATLAB (The MathWorks, Natick, MA). The first 10s of each time serie were removed from the analysis. For all analyses, in the time and frequency domain, the data was filtered using a low-pass 2nd order Butterworth filter of  $1.5Hz$  cut-off frequency.

### 2.4.1 Minimization of Sway Performance

Center of Mass (COM) data was used to quantify the performance of the participants in the voluntary minimization of sway task. The Root Mean Square of COM Velocity was computed in the AP direction for the eight conditions. We chose to use the Center of Mass instead of the Center of Pressure. The COM represents an approximation of the movement of the body, the sway, while the COP reflects ankle torque. Participants are asked to minimize sway and are not given any direct information or instruction concerning the Center of Pressure trajectories or velocities.

If a significant effect of instruction was found, the relationship between sway velocity during the relaxed condition and the ability to reduce sway was investigated. The correlation (*pearson correlation* using *R software*) of the percentage of reduction and the relaxed baseline was computed for each sensory condition.

### 2.4.2 Center of Pressure Frequency Analysis

Center of Pressure trajectories were studied in the frequency domain as Center of Pressure reflects the correcting activity and not only the sway of the body. As previously explained, it is likely that Instruction and Sensory context impact postural control differently depending on the frequency band studied.

COP PSD estimates were calculated for each participant and for all participants pulled together. For each participant and for all participants pulled together, one PSD estimate was calculated for each condition.

The PSD estimates were analysed on different frequency ranges. The spectrum was divided into two parts : low frequencies ( $[0.04 - 0.5Hz]$ ) and high frequencies ( $[0.5 - 1.5Hz]$ ). This decomposition is explained in Chapter 2 and was validated in the previous chapter. The frequency band corresponding to the drift ( $[0.04 - 0.1Hz]$ ) was isolated to further examine the effect of Instruction, Vision and Grip on the drift. Total Power was computed for each range as well as the entire range ( $[0.04 - 1.5Hz]$ ). For more detail, please refer to Chapter 2.

### 2.4.3 Modification of the Amount of Movement around the Hip Joint

A modification of the amount of movement around the hip joint can be identified by analysing the correlation of the hip and shoulder positions (using a small-angle approximation).

- positive correlation and "close" to 1 : predominant displacement of the shoulder and hip in the same direction
- negative correlation and "close" to -1 : predominant displacement of the shoulder and hip in opposed direction
- a modification from 1 and -1 toward -1 indicates an increased movement around the hip joint

## 2.5 Statistical Analysis

*R* software was used for the statistical Analysis.

For each statistical procedure, The Shapiro Wilk test was used to check the normality of the collected data. Log ( $\log_{10}$  and  $\text{logit}$ ) transformations were used for non normal residuals.

3-way (2x2x2) repeated-measures ANOVA with Instruction, Grip and Vision as factors were used to study the influence of Instruction, Grip, Vision and their various interactions on sway velocity, COP Power and amount of hip use. Post-hoc t-tests were used if significance was reached. The threshold for statistical significance was set to  $p = .05$ . P-values were adjusted using the Bonferroni multiple testing correction method.

It should be noted that for each condition, time-domain scores were determined from three trials.

As most statistical analyses are quite long given the three factors and interactions, most analyses are in the appendix [B](#).

## 2.6 Summary

In short :

- We study the minimization of sway in different sensory contexts;
- 13 participants were asked to stand upright either relaxed or actively minimizing their sway (staying still) for 1-minute trials with or without Light Grip and with or without Vision;
- COM Velocity, COP Power on different frequency bands and modification of the amount of movement around the hip joint ;

### 3 Results

#### 3.1 Minimization of Sway Performance

The displacement of the COM in the AP direction for all 8 conditions for a representative participant is shown in Figure 2.

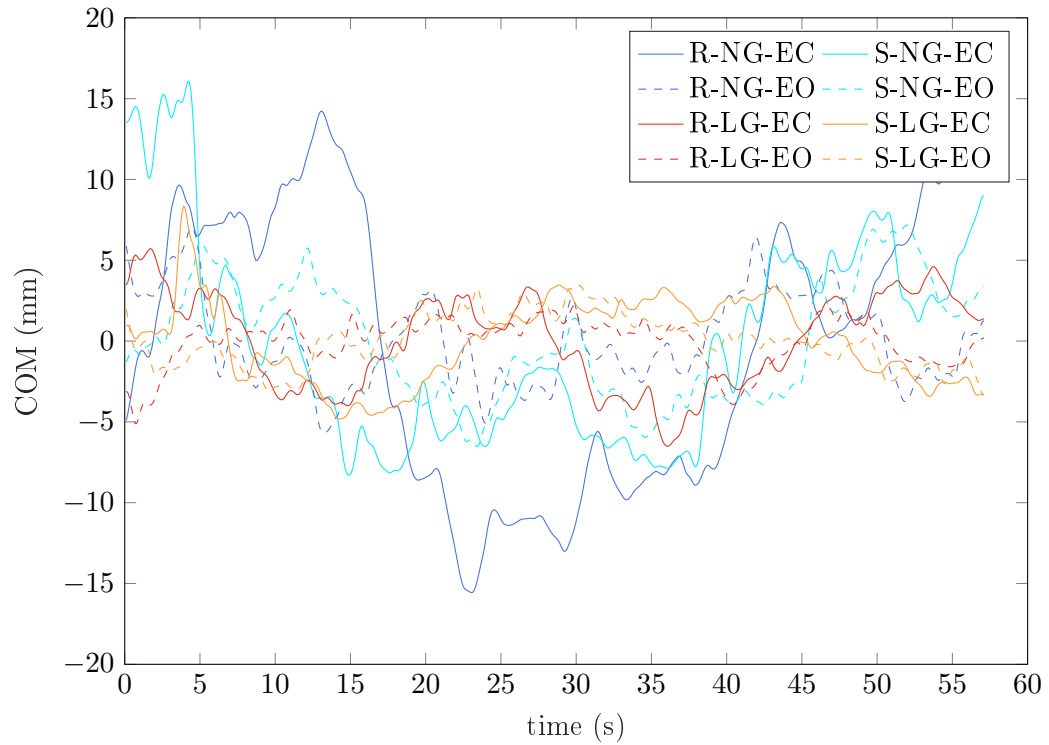


FIGURE 2: COM displacement amplitude in the time-domain for each condition (S : Still ; R : Relaxed ; NG : No Grip ; LG : Light Grip ; EC : Eyes Closed ; EO : Eyes Open) for one representative participant.



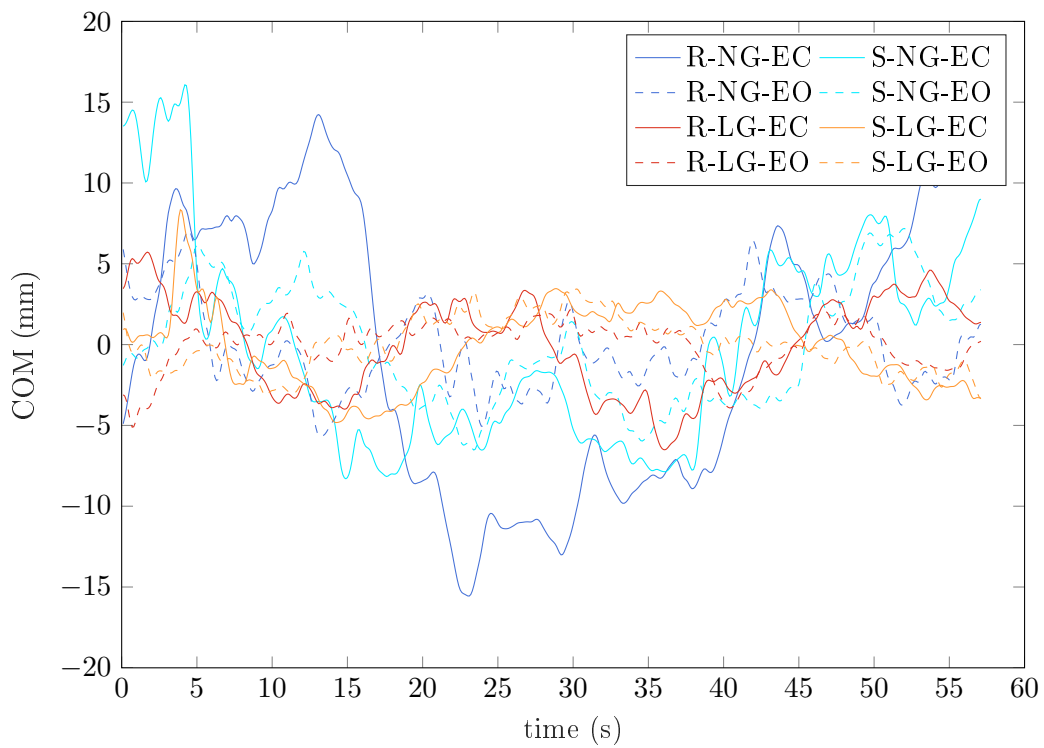


FIGURE 3: COM displacement amplitude in the time-domain for each condition (S : Still; R : Relaxed; NG : No Grip; LG : Light Grip; EC : Eyes Closed; EO : Eyes Open) for one representative participant.

RMS COM Velocity was used as an index of the performance of participants in the sway minimization task. The results are shown in figure 4.

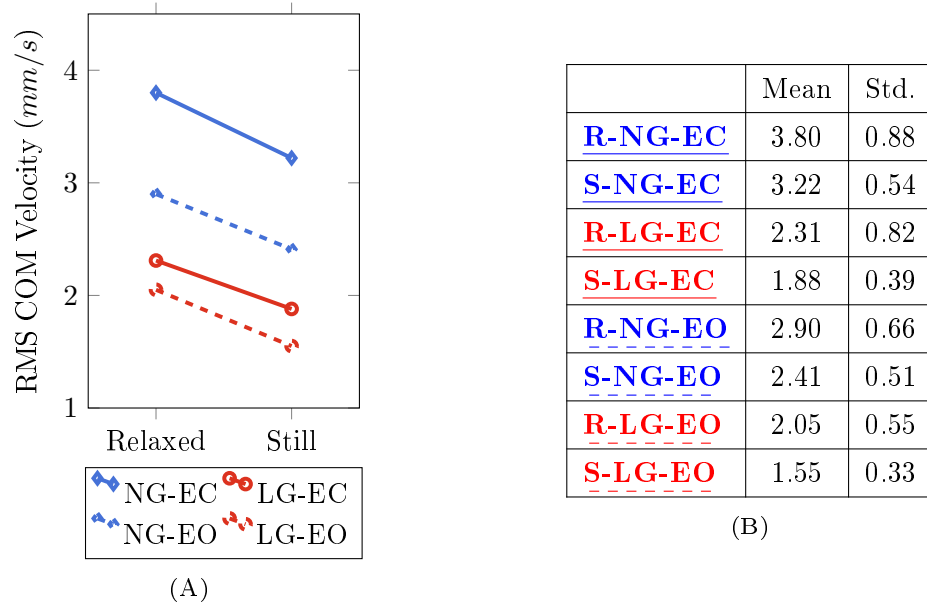


FIGURE 4: RMS COM Velocity for all conditions for all participants in (A). The descriptive Statistics (Mean and Standard deviation) of the RMS COM Velocity for the 13 participants are in (B) with **R** : **Relaxed**; **S** : **Still**; **NG** : **No Grip**; **LG** : **Light Grip**; **EC** : **Eyes Closed** and **EO** : **Eyes Open**. The effect of Grip can be observed by comparing the blue and red lines, the effect of vision by comparing the full and dashed lines and the slopes inform on the effect on the instruction.

**Observations** In figure 4, Light Grip conditions shown in red are below No Grip conditions shown in blue. Eyes Open conditions shown in dashed lines are below Eyes Closed conditions in full lines. The slopes of reduction between Relaxed and Still are very similar for all sensory contexts.

**Statistical Analysis** A three-way repeated measures ANOVA was performed to evaluate the effects of Instruction, Vision and Grip on RMS COM Velocity. The main effects of Instruction, Grip, Vision and the interaction of Grip and Vision are detailed in the appendix B as well as the pair-wise comparisons.

**Summary** The analysis of the RMS COM Velocity shows that participants were able to voluntarily reduce their sway velocity (main effect of instruction **S** < **R**) and this regardless of the sensory context (with or without Grip and with or without Vision).

The reduction was not impacted by the sensory context (no interaction of Instruction and Sensory context). This means that the reduction in terms of difference in mean between Relaxed and Still Stance for a specific sensory condition was the same as for another sensory condition. In other words, sway velocity was reduced of the same amount for No Grip Eyes Open, No Grip Eyes Closed, Light Grip Eyes Open and Light Grip

Eyes Closed. This can be observed by looking at the parallel slopes. The amount of sway velocity is however different between the different sensory conditions. This means that a participant relaxed with eyes closed can reduce sway if asked to minimize it without opening his/her eyes or lightly gripping a handle but the reduction would be greater if he/she opened his/her eyes and/or Lightly gripped the handle while voluntarily reducing.

We cannot say from this analysis that Grip or Vision were used to voluntarily reduce sway velocity as there is no interaction between the instruction and the sensory context. However, as the means in relaxed stance are different, a similar reduction in terms of difference in mean implies a different percentage of reduction. This would mean that the percentage of reduction is greater for Light Grip conditions than No Grip conditions.

Furthermore, we found that Sway velocity was reduced with Vision ( $\mathbf{EO} < \mathbf{EC}$ ) and Light Grip ( $\mathbf{LG} < \mathbf{NG}$ ) and that both had a greater effect in the absence of the other (interaction of Vision and Grip). Sway velocity was smallest for Light Grip conditions in the Relaxed and Still conditions. The effect of Vision for each Grip can be observed by comparing the space between full and dotted lines for blue and red lines respectively. The effect of Grip for each visual condition can be observed by comparing the space between the blue and red lines for full and dotted lines respectively.

	Pairs	P-value
Instruction	<u>R-NG-EC</u> vs <u>S-NG-EC</u>	$p = .032$ ↘
	<u>R-LG-EC</u> vs <u>S-LG-EC</u>	$p = .011$ ↘
	<u>R-NG-EO</u> vs <u>S-NG-EO</u>	$p = .009$ ↘
	<u>R-LG-EO</u> vs <u>S-LG-EO</u>	$p < .001$ ↘
Grip	<u>R-NG-EC</u> vs <u>R-LG-EC</u>	$p < .001$ ↘
	<u>R-NG-EO</u> vs <u>R-LG-EO</u>	$p < .001$ ↘
	<u>S-NG-EC</u> vs <u>S-LG-EC</u>	$p < .001$ ↘
	<u>S-NG-EO</u> vs <u>S-LG-EO</u>	$p < .001$ ↘
Vision	<u>R-NG-EC</u> vs <u>R-NG-EO</u>	$p < .001$ ↘
	<u>R-LG-EC</u> vs <u>R-LG-EO</u>	$p = .018$ ↘
	<u>S-NG-EC</u> vs <u>S-NG-EO</u>	$p < .001$ ↘
	<u>S-LG-EC</u> vs <u>S-LG-EO</u>	$p < .001$ ↘

TABLE 1: P-values of the post-hoc t-test pairwise comparisons of the RMS COM Velocity. Arrows indicate the direction of the change between the first and second part of the pair.

### 3.2 Correlation of the Relaxed Baseline and the Percentage of Reduction

The correlation of the relaxed sway velocity and of the percentage of reduction was computed. The fitted regression lines for all significant correlations are plotted on the figure 5 along the ratio of reduction as a function of relaxed baseline for all participants.

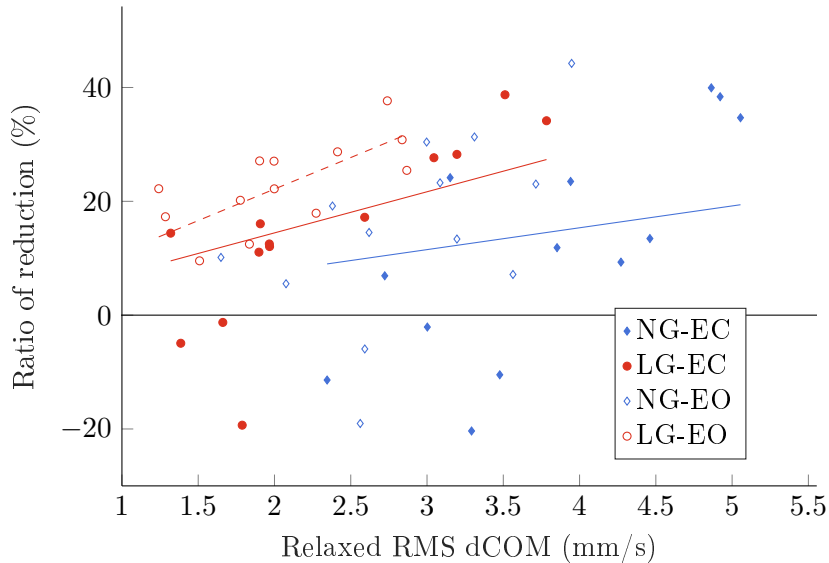


FIGURE 5: Percentage of reduction of RMS COM Velocity between Still and Relaxed Instructions for all sensory conditions as a function of Relaxed RMS COM Velocity. Each point of each color represents the ratio of reduction of one participant. **NG : No Grip, LG : Light Grip, EC : Eyes Closed, EO : Eyes Open**. Fitted regression lines are shown except for NG-EO as significance was not reached.

**Observations** Light Grip Eyes Open is the only sensory condition with only reduction of sway velocity and no increase of sway velocity over all participants. It seems that the greater the relaxed velocity, the greater the percentage of reduction over participants. Light Grip Eyes Open points are closer together than other sensory conditions like No Grip Eyes Closed and No Grip Eyes Open which are widely spread.

**Statistical Analysis** We found a positive correlation for all sensory conditions except No Grip Eyes Open.

- No Grip Eyes Closed :  $r^2 = 0.75$  and  $p = .003$  ;
- Light Grip Eyes Closed :  $r^2 = 0.81$  and  $p = .0008$  ;
- Light Grip Eyes Open :  $r^2 = 0.67$  and  $p = .013$ .

For No Grip Eyes Open, the correlation was not significant ( $p = .058$ ). The correlation value associated was of  $r^2 = 0.54$ .

**Summary** The observation of the percentage of reduction for each participant for each condition shows that while the instruction has a significant effect, not all participants present a reduction of sway velocity.

Light Grip Eyes Open, condition that showed the least amount of sway in mean, is the only sensory condition for which all participants were able to voluntarily reduce their sway whereas in other sensory conditions, some participants (2 to 4 depending on the sensory conditions) increased their sway velocity when asked to stand still compared to when asked to stand relaxed.

For all sensory conditions except No Grip Eyes Open, the correlation coefficient of the relaxed sway velocity and the percentage of reduction is positive. This means that participants who sway more (greater sway velocity) show a greater scope for reduction of sway velocity.

### 3.3 COP : A look into Sway Amplitude and Correcting activity

For each condition, COP PSD estimates were computed for all participants as well as for all participants pooled together to get an overall look.

The COP displacement for each condition in the time-domain for one representative participant is presented in Figure 6.

Figure 7 shows the PSD estimates for all participants pooled together except for one participant excluded (the data was not removed from the analysis). The behaviour of the PSD estimates were similar to the other participants but the values were distinctly greater than the other participants'. The PSD plots of the different participants are in Appendix B.

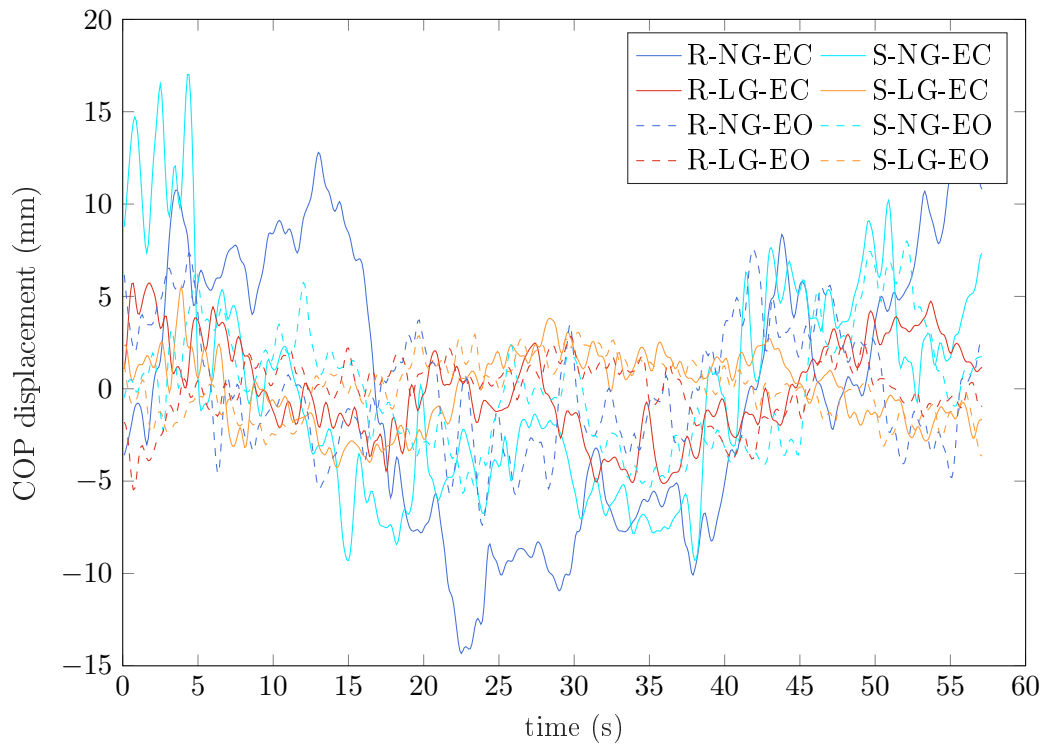


FIGURE 6: COP displacement amplitude in the time-domain for each condition (S : Still; R : Relaxed; NG : No Grip; LG : Light Grip; EC : Eyes Closed; EO : Eyes Open) for one representative participant.

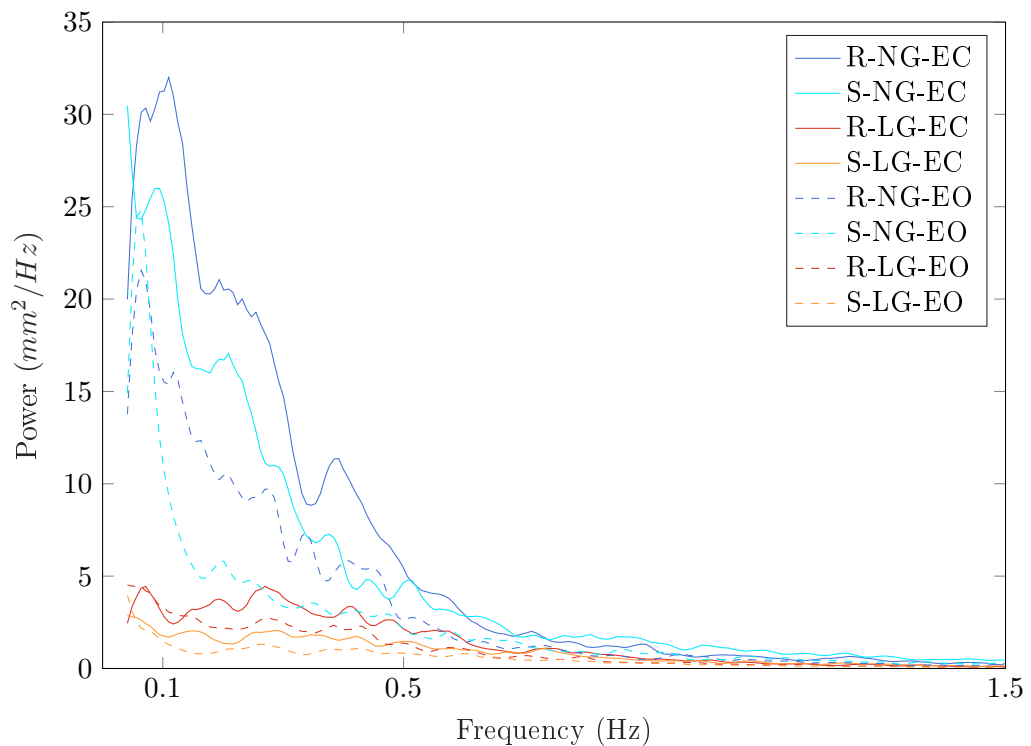


FIGURE 7: COP Power Spectral Density estimates for each condition (S : Still; R : Relaxed; NG : No Grip; LG : Light Grip; EC : Eyes Closed; EO : Eyes Open) for all participants pooled together except participant excluded.

We can see on Figure 7 that the Power is greatest for low frequencies. This is especially visible for the No Grip conditions. Light Grip conditions shown in light and dark red are below No Grip condition shown in light and dark blue. For each sensory condition, it can be observed on figure 7 that still PSD are lower than Relaxed PSD. The PSD plots are in line with visual inspection of the time-domain representation of the COP displacement for each condition in Figure 6 .

For all participants, there were no clear bumps for frequencies around 3 to 5Hz that would indicate deliberate sway (Latash, Ferreira, Wiczorek, & Duarte, 2003).

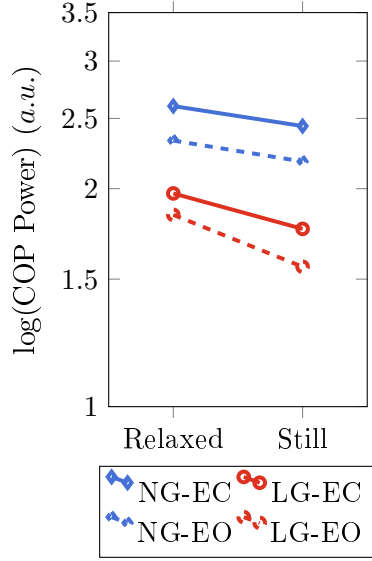
The statistical analysis of the COP Power is divided into several parts based on frequency bands. The COP Power was analysed for the entire frequency range as well as the 3 bands previously presented :

- Entire Frequency range :  $[0.04 - 1.5Hz]$  ;
- Low Frequency band :  $[0.04 - 0.5Hz]$  ;
- Drift band :  $[0.04 - 0.1Hz]$  ;
- High Frequency band :  $[0.5 - 1.5Hz]$ .

Boxplot of the COP Power for all conditions before log-transformation for all the frequency bands are in appendix B.

### 3.3.1 Center Of Pressure Power on the entire frequency range

Mean COP Power for the entire frequency range ( $[0.04 - 1.5Hz]$ ) for all participants are presented in Figure 8A. The mean and standard deviations are in Table in the Subfigure 8B.



(A) COP Frequency Power

Condition	Mean	Std.	N
<b>R-NG-EC</b>	2.54	0.21	13
<b>S-NG-EC</b>	2.35	0.17	13
<b>R-LG-EC</b>	1.85	0.33	13
<b>S-LG-EC</b>	1.58	0.25	13
<b>R-NG-EO</b>	2.27	0.19	13
<b>S-NG-EO</b>	2.08	0.19	13
<b>R-LG-EO</b>	1.73	0.33	13
<b>S-LG-EO</b>	1.38	0.24	13

(B) Descriptive Statistics (Mean and Standard deviation) of the COP Power

FIGURE 8: COP Power for the entire frequency range in (A) for all conditions for all participants in log scale. Means and Standard deviations of all conditions and for all N participants are shown in (B) with **R** : Relaxed, **S** : Still, **NG** : No Grip, **LG** : Light Grip, **EC** : Eyes Closed and **EO** : Eyes Open. The effect of Grip can be observed by comparing the blue and red lines, the effect of vision by comparing the full and dashed lines and the slopes inform on the effect on the instruction.

**Observations** The mean values for the Light Grip conditions are clearly inferior the No Grip mean values. The slopes of the Light Grip segment are steeper than the No Grip slopes, especially the Light Grip Eyes Open implying that the effect of instruction is greater for Light Grip than No Grip. Eyes Open segments are below Eyes Closed segments implying an effect of vision. The space between Relaxed Light Grip Eyes Closed and Relaxed Light Grip Eyes Open is not the same as Relaxed No Grip Eyes Closed and Relaxed No Grip Eyes Open, this supposes an interaction of Grip and Vision with a greater effect of Vision in the absence of Grip.

**Statistical Analysis** A three-way repeated measures ANOVA was performed to evaluate the effects of Instruction, Vision and Grip on the power on the entire frequency range ( $[0.04 - 1.5Hz]$ ). The analysis reveals a main effect of Grip, Vision and instruction and two interactions, the interaction of Vision and Grip and the interaction of Grip and



Instruction. The p-values of the post-hoc t-test pairwise comparisons are summarized in figure 2.

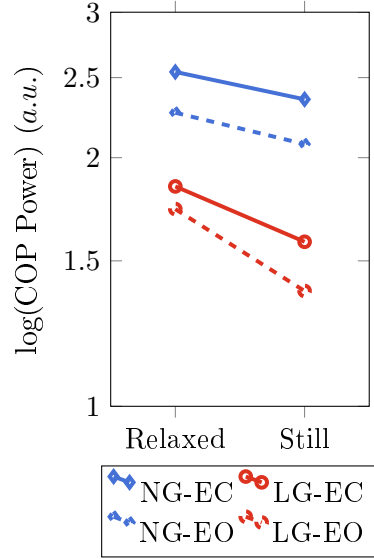
**Summary** The analysis on the entire frequency range shows that COP Power is reduced with Light Grip compared to No Grip (**LG < NG**), that COP Power is reduced with Eyes Open compared to Eyes Closed (**EO < EC**) and is reduced with the Instruction to stand Still compared to the instruction to stand Relaxed (**S < R**).

Furthermore, the analysis showed that the effect of Grip (reduction with LG compared to NG) was greater with Eyes Closed than Eyes Open. An analog comparison was found for Vision : the effect of Vision (reduction with EO compared to EC) was greater with No Grip than Light Grip. In brief, the **effect of one sensory information (either Grip or Vision) is greater in the absence of the other.**

Finally, the analysis showed that the effect of Instruction (reduction with Still compared to Relaxed) was greater with Light Grip than No Grip (**interaction Grip x Instruction**). In other words, the **reduction observed with the instruction was greater in presence of Light Grip cues.**

### 3.3.2 Center Of Pressure Power on the low frequency band

Mean COP Power for the low frequency band ( $[0.04 - 0.5Hz]$ ) for all participants is presented in Figure 9A. The mean and standard deviations are in Table in the Subfigure 9B.



(A) COP Frequency Power

Condition	Mean	Std.	N
<u>R-NG-EC</u>	2.54	0.21	13
<u>S-NG-EC</u>	2.35	0.17	13
<u>R-LG-EC</u>	1.85	0.33	13
<u>S-LG-EC</u>	1.58	0.25	13
<u>R-NG-EO</u>	2.27	0.19	13
<u>S-NG-EO</u>	2.08	0.19	13
<u>R-LG-EO</u>	1.73	0.33	13
<u>S-LG-EO</u>	1.38	0.24	13

(B) Descriptive Statistics (Mean and Standard deviation) of the COP Power

FIGURE 9: COP Power for the low frequency band in (A) for all conditions for all participants in log scale. Means and Standard deviations of all conditions and for all N participants are shown in (B) with **R** : **Relaxed**, **S** : **Still**, **NG** : **No Grip**, **LG** : **Light Grip**, **EC** : **Eyes Closed** and **EO** : **Eyes Open**. The effect of Grip can be observed by comparing the blue and red lines, the effect of vision by comparing the full and dashed lines and the slopes inform on the effect on the instruction.

**Observations** The mean values for the Light Grip conditions are clearly inferior the No Grip mean values. The slopes of the Light Grip segment are steeper than the No Grip slopes implying that the effect of instruction is greater for Light Grip than No Grip. Eyes Closed and Eyes Open segment are further away than for the drift band. Eyes Open segments are below Eyes Closed segments.

**Statistical Analysis** A three-way repeated measures ANOVA was performed to evaluate the effects of Instruction, Vision and Grip on the power on the low frequency band ( $[0.04 - 0.5Hz]$ ). The analysis revealed of main effect of Grip, Vision and instruction and two interactions, a interaction of Vision and Grip and of Grip and Instruction. The p-values of the post-hoc t-test pairwise comparisons are summarized in figure 2.

**Summary** The analysis on the low frequency band shows that COP Power is reduced with Light Grip compared to No Grip (**LG** < **NG**), that COP Power is reduced with

Eyes Open compared to Eyes Closed (**EO** < **EC**) and is reduced with the Instruction to stand Still compared to the instruction to stand Relaxed (**S** < **R**).

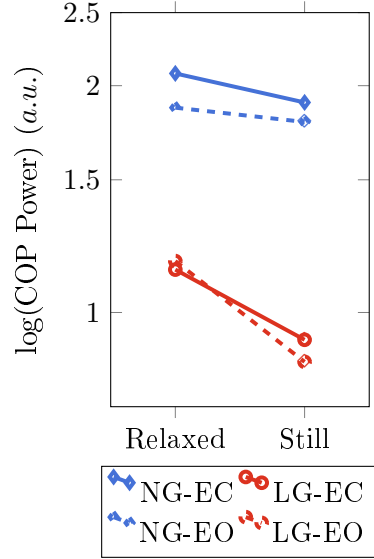
Furthermore, the analysis showed that the effect of Grip (reduction with LG compared to NG) was greater with Eyes Closed than Eyes Open. An analogue interaction was found for Vision : the effect of Vision (reduction with EO compared to EC) was greater with No Grip than Light Grip. In brief, the **effect of one sensory information (either Grip or Vision) is greater in the absence of the other.**

Finally, the analysis showed that the effect of Instruction (reduction with Still compared to Relaxed) was greater with Light Grip than No Grip. In other words, the **reduction observed with the instruction was greater in presence of Light Grip cues.**

Similar results were obtained for the entire frequency range.

### 3.3.3 Center Of Pressure Power on drift band

Mean COP Power for the drift band ( $[0.04-0.1Hz]$ ) for all participants are presented in Figure 10A. The mean and standard deviations are in Table in the Subfigure 10B.



(A) COP Frequency Power

Condition	Mean	Std.	N
<b>R-NG-EC</b>	2.07	0.27	13
<b>S-NG-EC</b>	1.90	0.20	13
<b>R-LG-EC</b>	1.14	0.44	13
<b>S-LG-EC</b>	0.92	0.40	13
<b>R-NG-EO</b>	1.87	0.27	13
<b>S-NG-EO</b>	1.79	0.22	13
<b>R-LG-EO</b>	1.17	0.48	13
<b>S-LG-EO</b>	0.86	0.34	13

(B) Descriptive Statistics (Mean and Standard deviation) of the COP Power

FIGURE 10: COP Power for the drift band in (A) for all conditions for all participants in log scale. Means and Standard deviations of all conditions and for all N participants are shown in (B) with **R** : **Relaxed**, **S** : **Still**, **NG** : **No Grip**, **LG** : **Light Grip**, **EC** : **Eyes Closed** and **EO** : **Eyes Open**. The effect of Grip can be observed by comparing the blue and red lines, the effect of vision by comparing the full and dashed lines and the slopes inform on the effect on the instruction.

**Observations** Eyes Closed and Eyes Open segments are very close, especially for Light Grip. The mean values for the Light Grip conditions are clearly inferior the No Grip mean values. The slopes of the Light Grip segment are steeper than the No Grip slopes implying that the effect of instruction is greater for Light Grip than No Grip.

**Statistical Analysis** A three-way repeated measures ANOVA was performed to evaluate the effects of Instruction, Vision and Grip on the COP Power on the frequency band corresponding to the drift ( $[0.04 - 0.1Hz]$ ). The analysis reveals a main effect of vision, of Grip and instruction and an interaction of Vision and Grip. The p-values of the post-hoc t-test pairwise comparisons are summarized in figure 2.

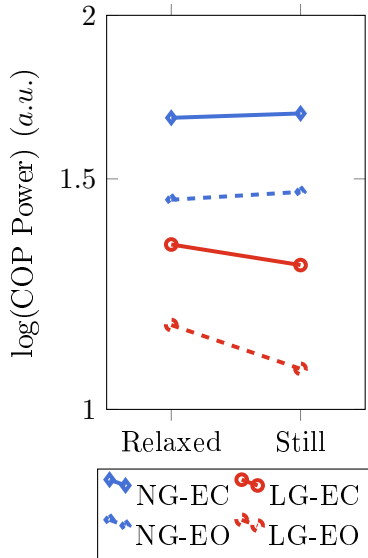
**Summary** The analysis on the drift band shows that COP Power is reduced with Light Grip compared to No Grip ( $LG < NG$ ).

COP Power is reduced with Eyes Open compared to Eyes Closed for the drift band only in relaxed stance and without Grip ( $\mathbf{R-NG-EO} < \mathbf{R-NG-EC}$ ). Vision had no significant effect for No Grip conditions.

COP Power is reduced with the Instruction to stand Still compared to the instruction to stand Relaxed for all sensory conditions except with Eyes Open and No Grip ( $\mathbf{S} < \mathbf{R}$  expect for  $\mathbf{NG-EO}$ ).

### 3.3.4 Center Of Pressure Power on the high frequency band

Mean COP Power for the high frequency band ( $[0.5 - 1.5Hz]$ ) for all participants are presented in Figure 11A. The mean and standard deviations are in the table in the Subfigure 11B.



(A) COP Frequency Power

Condition	Mean	Std.	N
<u>R-NG-EC</u>	1.67	0.19	13
<u>S-NG-EC</u>	1.68	0.23	13
<u>R-LG-EC</u>	1.34	0.27	13
<u>S-LG-EC</u>	1.29	0.22	13
<u>R-NG-EO</u>	1.45	0.23	13
<u>S-NG-EO</u>	1.47	0.15	13
<u>R-LG-EO</u>	1.16	0.22	13
<u>S-LG-EO</u>	1.07	0.21	13

(B) Descriptive Statistics (Mean and Standard deviation) of the COP Power

FIGURE 11: COP Power for the drift band in (A) for all conditions for all participants in log scale. Means and Standard deviations of all conditions and for all N participants are shown in (B) with **R** : Relaxed, **S** : Still, **NG** : No Grip, **LG** : Light Grip, **EC** : Eyes Closed and **EO** : Eyes Open. The effect of Grip can be observed by comparing the blue and red lines, the effect of vision by comparing the full and dashed lines and the slopes inform on the effect on the instruction.

**Observations** The slopes of all sensory conditions are almost flat except perhaps Light Grip Eyes Open with a slight descending slope. The mean values for the Light Grip conditions are inferior to the No Grip mean values. Eyes Open segments are below Eyes Closed segments.

**Statistical Analysis** A three-way rm ANOVA was performed to evaluate the effects of Instruction, Vision and Grip on the COP power on the high frequency band ( $[0.5 - 1.5Hz]$ ). The analysis revealed a main effect of Grip and Vision. The p-values of the post-hoc t-test pairwise comparisons are summarized in Table 2.

**Summary** The analysis on the high frequency band shows that COP Power is reduced with Light Grip compared to No Grip ( $\mathbf{LG} < \mathbf{NG}$ ), is reduced with Eyes Open compared to Eyes Closed ( $\mathbf{EO} < \mathbf{EC}$ ) but that COP Power is not modified with the Instruction to stand Still compared to the instruction to stand Relaxed ( $\mathbf{S} \approx \mathbf{R}$ ).

Contrary to the other frequency bands and entire range, the reduction observed with Light Grip or Eyes Open is not impacted by the presence or absence of the other.

### 3.3.5 Summary of the analysis on the different frequency bands

**Concerning the effect of instruction** The effect of instruction on COP Power was only present for the low frequency and drift band but not for the high frequency band. The power of the low frequency and drift band was reduced with the instruction (except No Grip Eyes Open for the drift band) whereas the power was unchanged for the high frequency band. There was a interaction of Grip and Instruction for the low frequency band and entire frequency range, the instruction to stand still had a greater effect for Light Grip than No Grip.

**Concerning the effect of the sensory context** For the effect of the sensory context, on the one hand, Grip had an effect on the entirety of the spectra studied. On the other hand, Vision had an effect mostly for the low frequency and high frequency bands ; Vision did not have an effect for the Light Grip conditions for the drift. Grip and Vision had a greater effect in the absence of the other, this was also the case the velocity of the Center of Mass.

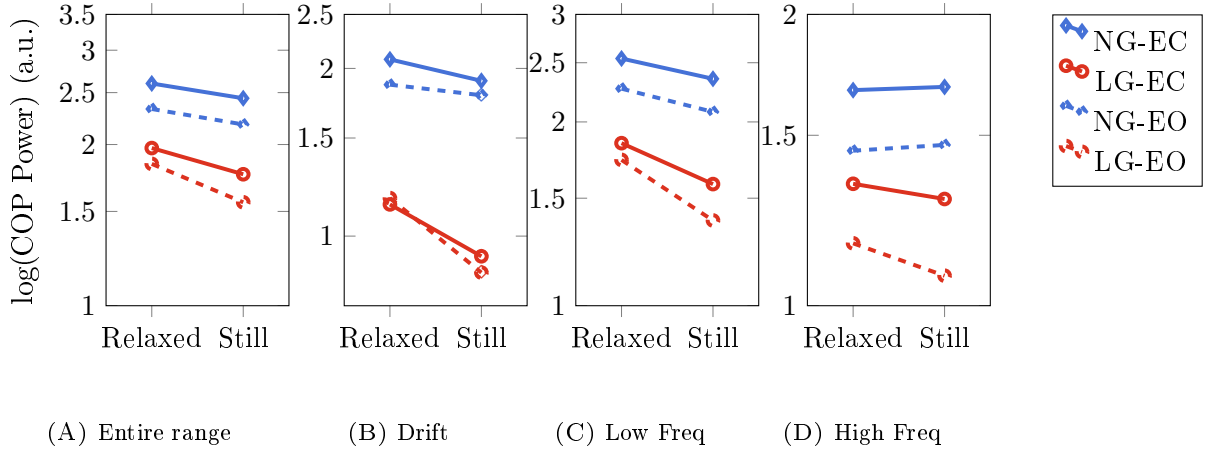


FIGURE 12: COP Power for the (A) entire frequency range (B) drift, (B) low frequency and (D) high frequency bands for all conditions for all participants. Blue Squares and red circles represent No Grip and Light Grip, respectively. Bold and dashed lines represent Eyes Closed and Eyes Open, respectively.

	Pairs	All Freq.	Drift	Low Freq.	High Freq.
Instruction	<b><u>R-NG-EC</u></b> vs <b><u>S-NG-EC</u></b>	$p = .008$ ↘	$p = .016$ ↘	$p = .004$ ↘	NME
	<b><u>R-LG-EC</u></b> vs <b><u>S-LG-EC</u></b>	$p < .001$ ↘	$p = .001$ ↘	$p < .001$ ↘	NME
	<b><u>R-NG-EO</u></b> vs <b><u>S-NG-EO</u></b>	$p = .011$ ↘	$p = .368$	$p = .005$ ↘	NME
	<b><u>R-LG-EO</u></b> vs <b><u>S-LG-EO</u></b>	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘	NME
Grip	<b><u>R-NG-EC</u></b> vs <b><u>R-LG-EC</u></b>	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘
	<b><u>R-NG-EO</u></b> vs <b><u>R-LG-EO</u></b>	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘
	<b><u>S-NG-EC</u></b> vs <b><u>S-LG-EC</u></b>	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘
	<b><u>S-NG-EO</u></b> vs <b><u>S-LG-EO</u></b>	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘
Vision	<b><u>R-NG-EC</u></b> vs <b><u>R-NG-EO</u></b>	$p < .001$ ↘	$p = .004$ ↘	$p < .001$ ↘	$p = .011$ ↘
	<b><u>R-LG-EC</u></b> vs <b><u>R-LG-EO</u></b>	$p < .001$ ↘	NME for LG	$p < .001$ ↘	$p = .015$ ↘
	<b><u>S-NG-EC</u></b> vs <b><u>S-NG-EO</u></b>	$p < .001$ ↘	$p = .05$	$p < .001$ ↘	$p < .001$ ↘
	<b><u>S-LG-EC</u></b> vs <b><u>S-LG-EO</u></b>	$p < .001$ ↘	NME for LG	$p < .001$ ↘	$p < .001$ ↘

TABLE 2: P-values of the post-hoc t-test pairwise comparisons for the three frequency bands and the entire frequency range. **R** : Relaxed, **S** : Still, **NG** : No Grip, **LG** : Light Grip, **EC** : Eyes Closed and **EO** : Eyes Open. Significant differences are in bold. Arrows indicate the direction of the change between the first and second part of the pair. NME : No Main Effect

### 3.4 Modification of the Amount of Movement around the Hip Joint

The correlation of hip and shoulder positions for eleven out of thirteen participants is shown in figure 13B. Two participants were excluded as too many data points were missing. As the correlation values were naturally between 0 and 1, the data was log transformed using the *logit* instead of the *log*<sub>10</sub>.

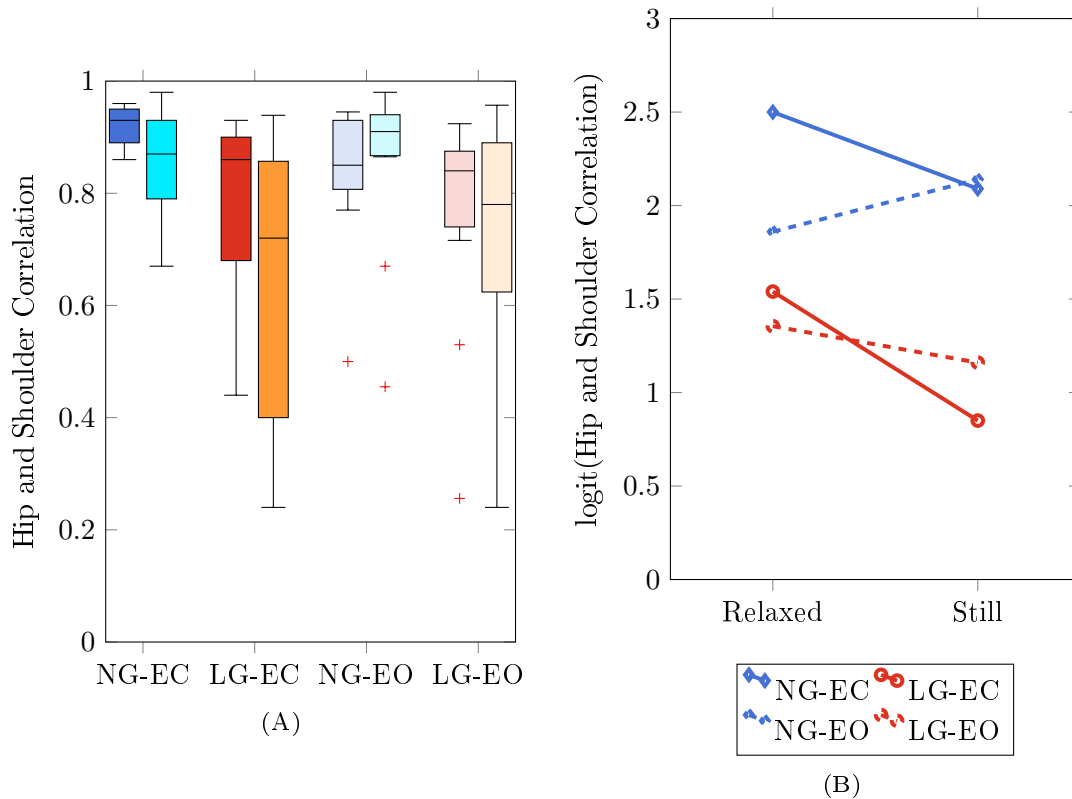


FIGURE 13: Correlation of hip and shoulder positions for 11 out of 13 participants : (A) Boxplot of the correlation of the hip and shoulder positions before log transformation for all conditions (NG : No Grip, LG : Light Grip, EO : Eyes Open, EC : Eyes Closed). Relaxed Conditions are shown in dark blue and dark red and Still in light blue and light red. Eyes Closed and Open conditions are in full color and transparent, respectively. (B) Correlation of the hip and shoulder positions for all conditions.

**Observations** The data before transformation is shown in figure 13A. On this boxplot, we can see that the variability of the value of the correlation is higher for the Light Grip conditions, especially with the Still Instruction. Distribution of the correlation are well above 0 for all conditions indicating a predominant movement around the ankles. An increased use of hip for Light Grip conditions seems possible, this is also visible in figure 13B where Light Grip conditions in red are below No Grip conditions in blue. Instruction segments with and without Vision lines are crossed. This suggests that an increased use of hip is more likely with the instruction to stand still in the absence of Vision but not in its presence (possible interaction of Instruction and Vision).



**Statistical Analysis** A three-way repeated measures ANOVA was performed to evaluate the effects of Instruction, Vision and Grip on the correlation of hip and shoulder positions.

The **two-way interaction between Instruction and Vision** was significant ( $F(1, 10) = 7.09, p = .024, \eta^2 = .022$ ). Vision had no significant effect on correlation for Relaxed ( $p = .07$ ) and Still ( $p = .087$ ) conditions with the adjustments. Instruction had no significant effect on correlation for Eyes Open ( $p = 1$ ) and for Eyes Closed ( $p = .098$ ) conditions with the adjustments.

**Grip had a significant main effect** on correlation ( $F(1, 10) = 22.61, p = .0007, \eta^2 = 0.179$ ). Pairwise comparisons show that Light Grip is significantly different from No Grip for all conditions ( $p = .002$  for Relaxed Eyes Closed,  $p = .029$  for Still Eyes Closed and  $p = .013$  for Still Eyes Open) except for Eyes Open Relaxed ( $p = .0203$ ).

**Summary :** There is an increased use of hip with Light Grip in still stance and with eyes closed in relaxed stance (**Light Grip : ↗ hip use except when eyes are open in relaxed stance (R-EO)**).

	Pairs	P-value
I	No main effect	
Grip	<u>R-NG-EC</u> vs <u>R-LG-EC</u>	<b><math>p = .002</math></b> ↘
	<u>R-NG-EO</u> vs <u>R-LG-EO</u>	$p = .203$
	<u>S-NG-EC</u> vs <u>S-LG-EC</u>	<b><math>p = .029</math></b> ↘
	<u>S-NG-EO</u> vs <u>S-LG-EO</u>	<b><math>p = .013</math></b> ↘
V	No main effect	

(A)

Condition	Mean	Std.	N
<u>R-NG-EC</u>	1.09	0.21	11
<u>S-NG-EC</u>	0.91	0.45	11
<u>R-LG-EC</u>	0.67	0.40	11
<u>S-LG-EC</u>	0.37	0.57	11
<u>R-NG-EO</u>	0.81	0.36	11
<u>S-NG-EO</u>	0.93	0.50	11
<u>R-LG-EO</u>	0.59	0.45	11
<u>S-LG-EO</u>	0.50	0.54	11

(B)

FIGURE 14: (A) P-values of the post-hoc t-test pairwise comparisons of the Hip and Shoulder correlation. Significant differences are in bold. **Arrows indicate the direction of the change between the first and second part of the pair.** I : Instruction ; V : Vision (B) Descriptive Statistics (Mean and Standard deviation) of the correlation after logit-transformation.

## 4 Discussion

In this experiment, we questioned the ability to voluntarily reduce sway in different sensory conditions. We asked 13 young and healthy adults to stand either relaxed or minimizing actively their sway with Light Grip or not and with Eyes Open or Eyes Closed.

We would like to highlight one of our findings. Light Grip can be used to reduce sway (Low Frequency COP Power) without an increase of high frequency COP Power.

We would like to summarize our results. We found that sway velocity could be voluntarily reduced regardless of the sensory information available (visual and light grip cues). The amount of sway velocity that can be reduced depends on the amount of sway in relaxed stance for each sensory conditions except No Grip Eyes Open. The greater the velocity in relaxed stance, the greater the reduction. Low Frequency COP Power is reduced with the instruction to minimize and the reduction is greater with Light Grip. Drift COP Power is not reduced with the instruction similarly for all sensory conditions (no reduction with No Grip Eyes Open). High frequency COP Power is not modified with the instruction to minimize sway. As for the influence of the sensory context for each stance. COP Power is reduced for all frequency bands (Drift, Low Frequency, High Frequency bands) with the addition of sensory information as well as the velocity of the COM. We also found an increased use of hip with Light Grip.

### 4.1 Voluntary Reduction of Sway Velocity

We found that when given the instruction to minimize sway, participants could actively reduce their sway velocity (RMS COM Velocity) whether or not visual and/or Grip information was available.

The voluntary reduction of sway velocity is in line with results from [Reynolds \(2010\)](#) and [Zok et al. \(2008\)](#). However, [Ueta et al. \(2015\)](#) found an increase of COP velocity. The difference between our results and [Ueta et al. \(2015\)](#) is surprising considering that the instructions provided to the participants were the same.

A closer look at the reduction of the velocity for each sensory condition for each participant shows that all participants were able to reduce sway when asked to minimize when they had their Eyes Open and Light Grip (LG-EO). This was not the case for the other sensory conditions.

Surprisingly, participants when asked to minimize sway reduced the velocity of their COM of the same amount regardless of visual or/and light Grip cues. [Reynolds \(2010\)](#)

found an interaction of the amount of reduction and vision and feet position stance. An inspection of the graphs presented in the study of Reynolds (2010) does not show a difference between Eyes Open and Eyes Closed for feet apart stance. This is the stance used in our study. It is possible that the impact of vision on the reduction might be more important for other stances.

We could conclude from this analysis that Sway can be voluntarily reduced and that the sensory condition does not have an impact on the effect of instruction. This absence of impact of sensory condition on sway reduction could be interpreted as a modified motor control strategy. However, COM velocity reflects the velocity of the sway of the body but it does not give much information about postural control mechanisms. First, when using the velocity, we overlook very low frequencies. Indeed, as showed in the previous chapter, the variability is greatest for low frequencies and more specifically, the drift (freq  $< 0.1Hz$ ), greatly reduced in velocity signals is greatly impacted by Grip. Secondly, the COM unlike the COP does not reflect the ankle torque and hence does not give any information to discuss neuromotor mechanisms or a modification of ankle joint stiffness or viscosity.

## 4.2 Investigation of the Mechanisms Possibly at Play in the Minimization of Sway

We computed the COP Power for different frequency bands : the entire frequency range ( $[0.04 - 1.5Hz]$ ), the drift ( $[0.04 - 0.1Hz]$ ), low frequency ( $[0.04 - 0.5Hz]$ ) and high frequency bands ( $[0.5 - 1.5Hz]$ ).

We found that when participants are asked to minimize sway, the low frequency power is reduced while the high frequency power is not modified. We found that Light Grip cues could be used to voluntarily reduce sway (interaction Grip x Instruction).

We will first present and discuss our results on the reduction of sway with the instruction to minimize sway in general before investigating the effect of the sensory context on the reduction with the instruction.

### 4.2.1 Influence of the Instruction on Low Frequency and High Frequency COP Power

For frequencies below  $0.5Hz$ , where the COP is similar to the COM, we found a reduction of COP Power. This means that the amplitude of the sway of the body was reduced with the instruction to stand still.

This result (reduction for frequencies  $< 0.5Hz$ ) is in line with Reynolds (2010) who found (observation of PSD plots) a reduction of power for frequencies below  $0.5Hz$ . Unfortunately, no quantitative analysis of the power and the impact of sensory context was reported. COP Power reduction for frequencies below  $0.5Hz$  is in line with Loram et al. (2001) and R. C. Fitzpatrick et al. (1992) who found a reduction of sway size (with the Still instruction vs relaxed instruction). Zok et al. (2008) found a significant reduction of COP range which is in line with our results. Ueta et al. (2015) did not find a reduction of COP power for frequencies between 0 and  $0.3Hz$ . Ueta et al. (2015) quantified COP variability using the mean frequency as well as a computation of the power on different frequency bands ( $[0 - 0.3Hz]$ ,  $[0.3 - 1Hz]$  and  $[1 - 3Hz]$ ). It is not clear whether very low frequencies that cannot be properly studied (around  $0Hz$ ) were removed before the analysis. It should be noted that keeping frequencies whose variability cannot be properly quantified might lead to errors in the analysis. Observations of a non-significant tendency of reduction of sway frequency of the low frequency range ( $0 - 0.3Hz$ ) is however in line with our results. It is possible that the choice of  $0.3Hz$  to separate frequency bands caused the effect of instruction to be non-significant because part of the effect might be "hidden" in the median frequency band.

For frequencies greater than  $0.5Hz$ , we found that the instruction to stand still caused no significant modification of COP power. This means that the frequency of the correcting activity was not increased with the instruction to minimize.

We would like to remind that when participants were asked to minimize their sway, the overall frequency content and the sway velocity were reduced.

Loram et al. (2001) propose an explanation on how sway is reduced during a minimization of sway task. They propose a reduction of ankle torque motor noise through an active predictive process instead of a modification of the stiffness or viscosity of the ankle joint. Feedforward mechanisms have been presented in the literature as necessary to compensate the delays in feedback loops and the impossibility for visco-elastic properties to maintain an upright stance alone (Gatev et al., 1999; Morasso & Schieppati, 1999). Our results are in line with this hypothesis. We do not have a measure of the co-contraction however, an increased stiffness seems unlikely. Sciada et al. (2016) compared the influence of two instructions on sway : the instruction of sway as little as possible and the instruction to sway as little as possible with an active and continuous stiffening. They found that the stiffening strategy increased sway variability in terms of amplitude of displacement and velocity. We found that COP power was reduced and that the velocity of the COM is also reduced. It is thus unlikely that the reduction is due to a stiffening. Moreover, it is indeed unlikely that a stiffening strategy would be efficient as the visco-elastic properties cannot stabilize stance (Morasso & Schieppati,

1999). Furthermore, we asked our participants if they believed that they had stiffened, most participants answered that they tried at first but abandoned this strategy very quickly as it was inefficient but also tiring. Finally, Reynolds (2010) found an increased co-contraction with the instruction to minimize sway compared to relaxed stance but it was not correlated with the reduction of sway. We can hypothesize that participants might have tried to stiffen but that it was not the main strategy or not the one chosen for most trials.

#### 4.2.2 The Use of Light Grip Cues in the Minimization Task

We observed that when participants were asked to minimize sway, the low frequency ( $< 0.5Hz$ ) COP Power was reduced. Furthermore, central to our study, we showed that Light Grip allowed a greater reduction of sway (interaction of Grip and Instruction on the Low frequency COP Power). This means that Light Grip likely provides sensory information that can be used to voluntarily reduce sway. We can hypothesize, in line with Loram et al that sway was minimized by an active predictive process using the sensory information provided by Light Grip. The use of Light Grip cues to reduce sway can be explained by the tactile and proprioceptive cues provided closer to the COM. Studies in the literature showed that Light Grip provides sensory information about body sway (Albertsen et al., 2010; Krishnamoorthy et al., 2002) and that Light Grip cues can be used to anticipate body motion (Dickstein et al., 2001; J. R. Lackner et al., 2000). Furthermore, the increased hip use for Light Grip conditions suggests that Light Grip provides a higher reference closer to the COM. This is in line with Franzén et al. (2011) or Assländer et al. (2018). The slope representing the change of the instruction (Relaxed  $\rightarrow$  Still) for correlation of hip and shoulder positions in Figure 13B is especially steep. This suggests that when there is only Light Grip, the voluntary reduction is done through the use of sensory information closer to the COM, the Light Grip cues.

While the Light Grip cues can be used to minimize sway, lightly gripping also adds a supra-postural task. This task is likely associated with an external focus possibly allowing a greater minimization with Light Grip. The instruction to stand still led to a decrease of Low Frequency COP Power but to no modification of High Frequency Power. The reduction of Low Frequencies observed with the addition of visual or Light cues in relaxed stance is accompanied by a reduction of High Frequencies as well. This suggests that the reduction was less efficient than the one happening in relaxed stance. We can hypothesize that the instruction to stand still added an internal focus. Wulf et al. (2001) or Vuillerme et Nafati (2007) explained that according to the *constrained action hypothesis*, consciously controlling one's movement (internal focus) could interfere with the coordination of automatic processes at play to regulate the movement. When

performing a supra-postural task, movements are usually controlled with the external result in mind (external focus). During Light Grip, participants had to lightly grip the handle and not just grip it. Most participants reported that it was not difficult but that it still required a bit of focus. It is possible that for Light Grip conditions, participants' focus was shifted. Light Grip likely added an external focus. [Mcnevin et Wulf \(2002\)](#) present the external focus associated to Light Touch. It is possible that participants minimized their sway because they were instructed to do so but the external focus associated with Light Grip helped them to minimize.

#### 4.2.3 The Use of Visual Cues in the Minimization Task

We found that vision does not allow a greater reduction of sway (no interaction of Vision and Instruction on the Low Frequency COP Power). This is not in line with the results of [Loram et al. \(2001\)](#) or [R. C. Fitzpatrick et al. \(1992\)](#) who found that vision allowed a greater reduction. This difference can perhaps be explained by the setup used by Fitzpatrick et al or Loram et al. In both studies, the device used did not allow oscillations of frequencies below  $0.1Hz$ . For the Drift band ( $< 0.1Hz$ ), we found that the COP Power was reduced with the instruction to minimize for all sensory conditions except for the No Grip Eyes Open condition. It is thus possible that by excluding this band, the impact of vision is clearer.

For the drift band, we found that No Grip Eyes Closed COP Power was reduced with the instruction to minimize sway. However, the No Grip Eyes Open COP Power was not significantly reduced with the instruction to minimize sway. When we look at the amount of sway in relaxed stance for No Grip Eyes Closed and No Grip Eyes Open, we can see that COP Power is reduced when eyes are open compared to closed. COP Power with No Grip Eyes Closed (S-NG-EC) in still stance is very similar to the COP Power for No Grip Eyes Open in relaxed stance (R-NG-EO) ( $R-NG-EC > R-NG-EO$  but  $S-NG-EC \approx R-NG-EO$ ). We can hypothesise, than in relaxed stance, opening the eyes reduces the drift to satisfy a supra-postural constraint. The information used is possibly only proprioceptive or both proprioceptive and visual. It thus possible that when participants are asked to minimize, they cannot reduce more with eyes open as the proprioceptive and visual cues have already been used to their full extent. Studies have shown the sway can be reduced to facilitate vision ([T. Stoffregen & Pagulayan, 2000](#)).

### 4.3 Hypotheses Explaining why Sway is Reduced with Visual and/or Light Grip Cues in Relaxed Stance

If a reduction of sway is possible, this means that sway was not minimized without the instruction to do so. Even though this is not quantifiable across all participants, almost all participants reported that they needed to focus to minimize sway and that they needed to remind themselves as it did not come naturally to them.

We found in line with many other studies ([Backlund Wasling et al., 2005](#) ; [Honeine et al., 2015](#)) that Sway was reduced with Light Grip and Vision in relaxed or still stance (depending on the instruction used during the experiment).

Given that sway minimization may not be the goal of postural control, we can thus question why sway is reduced with the addition of Vision or Light Grip in relaxed stance.

We rarely stand without doing anything. Vision as touch are at the core of many activities. It is possible that postural control is modulated to facilitate Vision and or Grip ([M. Riley et al., 1999](#) ; [T. Stoffregen & Pagulayan, 2000](#)). As the supra-postural tasks and the minimization are both in favour of a reduction of the oscillations, we cannot separate the influence of the supra-postural and the sensory information. We can however say that the entire effect cannot be attributed to the supra-postural task as the reduction of sway with the instruction to minimize is greater with Light Grip.

We computed the correlation of the amount of reduction (percentage) for each sensory condition with the relaxed baseline of the same sensory condition. We found that for all conditions, the correlation was significant and positive except for No Grip Eyes Open. A positive correlation means that the greater the velocity in the relaxed conditions, the greater the percentage of reduction with the instruction to stand Still. [Reynolds \(2010\)](#) found a significant and positive correlation for Eyes Closed and Eyes Open for feet apart (No Grip). The difference in our results is not very strong as significance was almost reached for the No Grip Eyes Open condition ( $p = .058$ ).

In short, participants who swayed more (greater COM Velocity) in relaxed stance were able to reduce more when asked to minimize. The exploratory theory ([Carpenter et al., 2010](#)) explains that we are swaying, in part, to gather sensory information. Our results are in line with the theory, participants who swayed more likely had more information to reduce hence the greater reduction. This suggests that the amount of sensory information that can be gathered by the sway defines the amount of sway in relaxed stance.

We can suppose that adding a sensory source requires less sway to gather it. Sway is thus reduced when we open the eyes and/or lightly grip a handle because we do not

need to sway as much to gather the sensory information. Light Grip Eyes Open is the condition with both Visual and Light Grip cues and the condition with the smallest sway.

We would like to compare the reduction afforded by Light Grip and Vision compared to the one observed when participants are asked to minimize. To clarify, we would like to propose an example. When a participant, either in relaxed or still stance, with eyes open and no grip is asked to lightly grip the handle, the low frequency and high frequency power is reduced. When the participant with eyes open and no grip is asked to minimize, the low frequency power is reduced while the high frequency power is not modified. This suggests that the reduction afforded by sensory information (NG -> LG and EC -> EO in relaxed or still stance) is more efficient and costs less effort than the reduction with the instruction to minimize (Relaxed -> Still stance). This suggests in line with theories on the external focus that the non-volitional reduction (no change of instruction) is more efficient than the volitional one (Relaxed -> Still).

Sensory information are likely used to reduce sway for stability purposes and sway is likely reduced to answer tasks requirements while considering the costs in terms of neuromuscular activity, cognitive load or metabolic costs.

## 5 Conclusion

We studied the voluntary minimization of sway in different sensory contexts, with or without Light Grip, with or without Vision. We found that voluntary sway minimization is possible without an increase of the COP high frequency content. The reduction of sway with the instruction to minimize suggests that sway minimization is not likely the goal of postural control. We found that the voluntary reduction is greater in presence of Light Grip. This suggests that Light Grip provides sensory information usable to control sway. The external focus likely associated with the supra-postural task of maintaining a Light Grip probably helped participants to minimize sway using sensory information.

We suggest, in line with other studies that feedforward mechanisms are probably used to voluntary control balance. The study of EMG activity and their timing could perhaps shed some more light on the mechanisms at play. Voluntary minimization of sway implies the cognitive penetrability of postural control. This voluntary reduction probably has a cost, metabolic or neural. This could be investigated using cognitive tasks. Their nature, whether or not they can be facilitated by a sway reduction and whether or not they are perceptual should be made clear. Furthermore, sway is reduced but we do not know how participants would react to disturbances, it would be interesting to compare the robustness of postural control with and without the instruction to minimize sway.



We would like to comment on the "natural" aspect of the instruction. Standing Still and Standing Relaxed are two "kinds" of postural control that can be almost qualified as "natural"/ecological. The ecological aspect of the control depends on the tasks and of the environment. When at the edge of a cliff, it seems relevant to reduce sway ([Carpenter, Frank, & Silcher, 1999](#)) while it seems less relevant when standing in a big room. While being similar to "ecological" control, it is rare in daily life to do nothing while standing. The absence of another task is rare. We think, in line with other researchers ([Bonnet, 2016](#)), that it is crucial to specify the instruction chosen when conducting an experiment on postural control as the instruction conditions the behaviour, the cognitive load and the focus of attention. The instruction should be carefully chosen as the two instructions present advantages and drawbacks. We would like to conclude that we showed that Light Grip cues can be use to voluntarily reduce sway. Whether sway can be minimized further is not answered.

## Chapitre 5

# Is Voluntary Control of Sway using a Hand Delivered Vibrotactile Biofeedback Possible ?

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We would like to investigate the influence of a Vibrotactile Biofeedback on the voluntary control of sway in presence or a grounded reference or not. The grounded reference and the biofeedback could be provided by a cane with an actuated handle. As in the previous chapter (Chapter 4), we use a task of minimization of sway.

## 1 Introduction

Light Grip as previously presented is considered to provide sensory information about the position and movement of the body in space. These information are provided close to the COM and are thus usually associated to an increased hip use (Franzén et al., 2011). As shown in the previous chapter (Chapter 4), Light Grip sensory information can be used to voluntarily reduce sway. Furthermore, it is considered that Light Grip is associated to an external focus of attention promoting a more automatic control and thus more efficient control of sway (Mcnevin & Wulf, 2002). The Grip will be referred as Grounded Grip as our biofeedbacks are delivered to the hand through a handle, the same handle that is attached to the ground or not.

A biofeedback system for balance aims at improving postural control. The underlying principle of these devices is to improve balance by supplementing native sensory input with coded information about body posture conveyed through sensory channels. The effect of biofeedbacks for balance can be explained by a reweighting of the "native" sensory information (Sienko et al., 2018). In other words, the already existing sensory information is given more weight because it is correlated to the information provided by the biofeedback.

It seems relevant for the design of biofeedback device to question the possible reweighting of Grounded Grip sensory information provided by a cane during the use of a biofeedback. The combination of Light Touch on the back and a vibrotactile biofeedback has been investigated by Saini et al. (2019). They found that for the biofeedback combined with the Light Touch sway was reduced to a greater extent than with only Light Touch only for the amplitude of the COP and not its velocity. However, in this experiment, the Light Touch was maintained by a robot and not by the participant. No external focus can thus be associated to this touch while the instruction to reduce sway is likely associated with an internal focus. An internal focus is considered to hinder an efficient and automatic control (Vuillerme & Nafati, 2007; Wulf et al., 2001). A Grounded Grip, where the participant needs to control the lightness his/her grip, can add an external focus and thus can likely promote a more efficient control (Mcnevin & Wulf, 2002). Furthermore, many vibrotactile biofeedbacks are delivered through a waist-band

while we are using the same handle used for the Grounded Grip. This has not been done to our knowledge.

We can hypothesise that biofeedback cues may be used to reweight Grounded Grip cues. Such a reweighting would induce a greater reduction of sway with the Biofeedback for a Grounded Grip than in absence of a grounded reference.

Many Biofeedbacks devices/systems for balance have been developed over the years. Many are tested and designed with a minimization of sway around one reference position. By constraining sway around one reference position, the participants' drift ( $< 0.1Hz$ ) is constrained.

We can question whether constraining sway around one reference position is ecological. The functional role of variability is discussed. Different theories explain that the movement is not the sign of instability but that it can be useful or simply not problematic stability-wise. Sway can be used to gather sensory information (*exploratory theory*). Furthermore, a slow movement of the body may be necessary for the control of sway using feedforward mechanisms (Gatev et al., 1999). Finally, if the movement of the body is not threatening the stability, it is not necessary to reduce it (*uncontrolled manifold*). Duarte and colleagues (Rasouli et al., 2017) explain that the drift in quiet stance does not threaten stability if within bounds. Postural control could perhaps be summarized as not falling while doing things and not not moving.

If we consider that variability is allowed to improve stability then a biofeedback "bringing" back the individual to a unique reference is adding a constraint while providing information. This constraint potentially non-ecological or unusual at least might hinder postural control rendering it less efficient and resulting possibly in an increase of the high frequencies of sway or an increased cognitive load or neuromuscular activity.

Goodworth et al. (2009) or Loughlin et al. (2011) showed that a position-driven biofeedback induces a decrease of Low Frequencies but an increase of High Frequencies ( $> 0.5Hz$ ). A position and velocity combined biofeedback induces a smaller decrease of Low Frequencies but a smaller increase or no increase of High Frequencies. While the comparison of position, velocity and a combination of both gives information about the effect of a reference position, constraining specifically the drift ( $< 0.1Hz$ ) with the same amount of allowed sway with only position-based information could be useful to investigate how the constraining of the drift specifically affects the performance.

We can hypothesise that a biofeedback constraining the drift might be less efficient than a biofeedback that does not constrain the drift of the individual.

**Our hypotheses** In this study, we investigate the use of two biofeedbacks, one constraining the drift of the participant and another, not constraining the drift, in a voluntary reduction of sway task. These biofeedbacks are tested in presence of absence of a Grounded Grip. Our two hypotheses are the following :

- Grounded Grip cues can be re-weighted by the biofeedback to reduce voluntarily sway. This means that the reduction afforded by the biofeedback would be greater with Grounded Grip than without Grounded Grip ;
- The biofeedback not constraining the drift will promote a more efficient reduction of sway than the one constraining the drift.

## 2 Methods

We want to study the effect of the Biofeedback and the effect of a Grip Grounded on not on the minimization of sway and the interaction between Grip (Grounded or not) and the Biofeedback on the minimization of sway. We chose to study a vibrotactile biofeedback that can be embedded in a handle and for other reasons presented in the State of the Art in section 4. The grounded handle is referred as Grounded Grip and the handle not grounded is referred as Air Grip. This kind of system, could be embedded, in the long term, in the handle of a cane, combining the passive (cane) and active (biofeedback device) assistive devices into one device instead of two or more.

In order to do this, we designed a device that provides supplemental Vibrotactile Biofeedback synchronized in real-time with a signal encoding information about the COP position in the AP direction. As previously mentioned, a minimization of sway task was used in this study. However, as the instructions and the specificities of the minimization task depend on the biofeedback used, the task will be detailed after the presentation of the biofeedbacks.

### 2.1 Participants

14 people (9 men and 5 women ; age =  $26.9 \pm 3.3$  years [ $M \pm SD$ ], height =  $173 \pm 8$  cm, 12 right-handed and 2 left handed) participated in the study. All participants were healthy and had no known neurological or muscular disorder. Participants gave informed consent.

## 2.2 Overview of the Setup

The experimental setup consists in a Vibrotactile Biofeedback System and a data collection system. The data collection system is presented after the Vibrotactile Biofeedback System.

A schematic representation of the setup is presented in Figure 1.

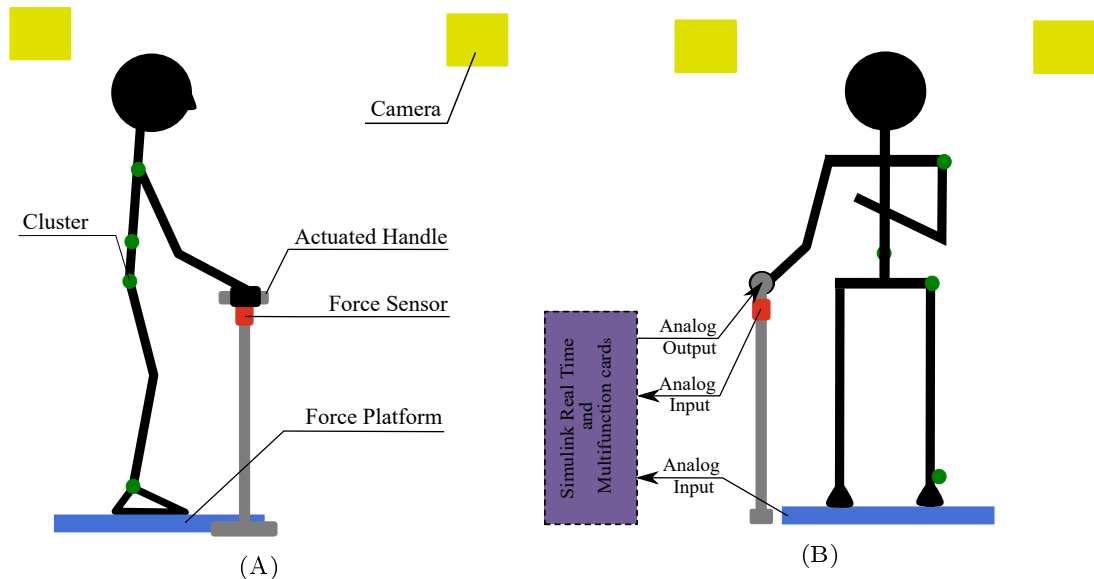


FIGURE 1: Side and Front View of the Experimental Setup

## 2.3 Overview of the Vibrotactile Biofeedback System

The Vibrotactile biofeedback (VBF) system consists of a handle delivering the vibrotactile biofeedback using two embedded vibrators (linear-coil actuators), a force platform to monitor the COP displacements (used to drive the biofeedback system), a Simulink Real Time computer with NI multifunction cards and audio amplifiers. The monitoring of the COP as well as the output of the biofeedback were sampled at  $4kHz$ .

The computation of the COP using force platform data is detailed by equation 2.2 in chapter 2.

The handle can be either rigidly fixed to the ground, next to the force platform, through an uniaxial force sensor or untethered to provide either Grounded Grip or Air Grip.

## 2.4 Human-Machine Interface of the VBF System

The human-machine interface of the VBF system is a cylindric handle made of two 3D printed parts separated by a small gap. Figure 2 presents the different parts of the handle.

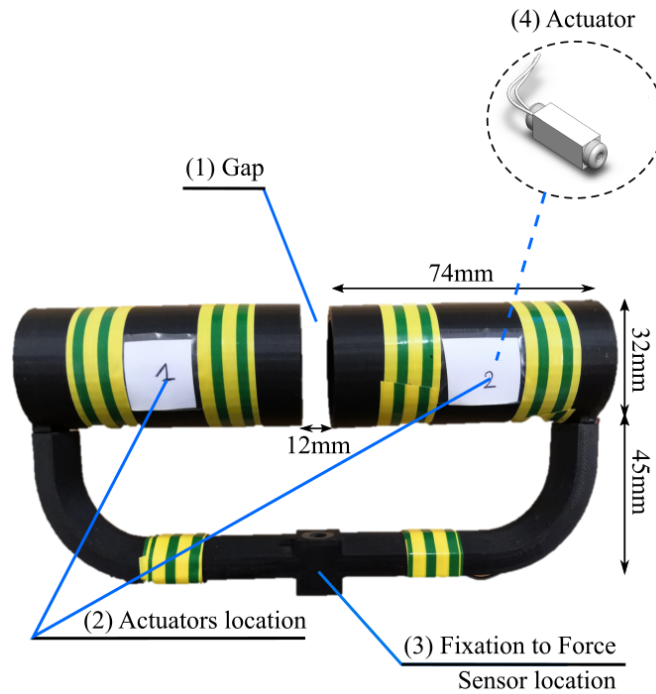


FIGURE 2: Human Machine Interface of the Vibrotactile Biofeedback System.

There is a vibrotactile actuator (linear-coil actuator) in each of the two parts of the handle. Their location is shown in the figure. The gap between the two parts limits the propagation of the vibration between the two parts. Both actuators were calibrated with an accelerometer so they would vibrate at the same amplitude and frequency for a given input.

The handle can be rigidly fastened on a uniaxial force sensor to monitor the force applied for the Grounded Grip condition.

One of the two biofeedbacks provides information about the direction of sway in the AP direction. Two actuators, one in the anterior and one in the posterior part are used to that end. A study by [Sienko et al. \(2010\)](#) showed that a more precise resolution of the direction was not necessary.

## 2.5 The Biofeedback Modes

As explained in the introduction, we investigated two different biofeedback modes.

Two different Biofeedback modes were used. One is constraining the drift of the participant COP and the other is not constraining the drift of the participant COP. The biofeedback constraining the drift will be referred as Drift Constraining or DC and the biofeedback not constraining the drift as Drift Free or DF.

For both biofeedbacks, the driving physiological signal is the position of the COP of the participant in the AP direction. Its computation and acquisition was explained in Chapter 2. Several studies (Halická et al., 2014; Kilby et al., 2016; Lakhani & Mansfield, 2015) show that both the COP and COM can be used for a minimization of sway and that the choice between the two does not influence much the result. Furthermore, it was more practical to use COP data.

For both modes, a vibratory biofeedback is provided if the COP exceeds a dead-Zone, a no-vibration zone. The Dead-Zone has an informative purpose. For the Drift-Constrained Biofeedback, the Dead-zone informs the participant of the position set-point. For the Drift-Free Biofeedback, the crossing of the Dead-Zone works as an alarm. Apart from the information provided, the presence of the DZ is more comfortable sensitivity-wise and stress-wise for the participants (Alahakone & Senanayake, 2010).

The DC Biofeedback is providing information about the position of the COP relative to a dead-zone fixed in position. The DF Biofeedback worked as an alarm if the COP was out of the Dead-zone, the position of the dead-zone is moving along the drift of the participant's COP.

We determine two DZ per participant, one for the Air-Grip trials and one for Grounded-Grip trials. The DZ are thus participant-specific and Grip-specific. As explained in the State of the Art, inter-subject variability is high, using a common threshold would likely end up in various effects that might not be the result of similar processes. If the same size was chosen for Air Grip and Grounded Grip trials then likely one of them would be too easy and/or too difficult.

Each participant performed 1 trial of 70s of each Grip condition without biofeedback with the instruction to minimize sway. After each trial was performed, the threshold was calculated. The COP displacement data were first filtered with a second order butterworth bandpass filter of 0.1 and 10Hz cut-off frequencies. This was done to remove the drift of the data. The root mean square COP displacement of each trial was then computed. This value was used as the threshold after multiplication by a gain of 1.2. This gain was used as the RMS alone was perceived as too difficult in preliminary tests with 2 individuals prior to the experiment. The computation is summarized in equation 2.5.

$$DZ = 1.2 * RMS(COP_{withoutDrift}) \quad (5.1)$$



The determination of the threshold for the Dead-zone is illustrated in Figure 3. We can see that the Dead-zone is computed on the signal without the drift. We can see that the Dead-Zone is slightly smaller than the amplitude of COP oscillations without drift. This means that both Biofeedbacks give information about the amplitude of COP oscillations for frequencies greater than  $0.1Hz$ . We can see on the last subfigure how the position of the dead-zone constraining or not the drift.

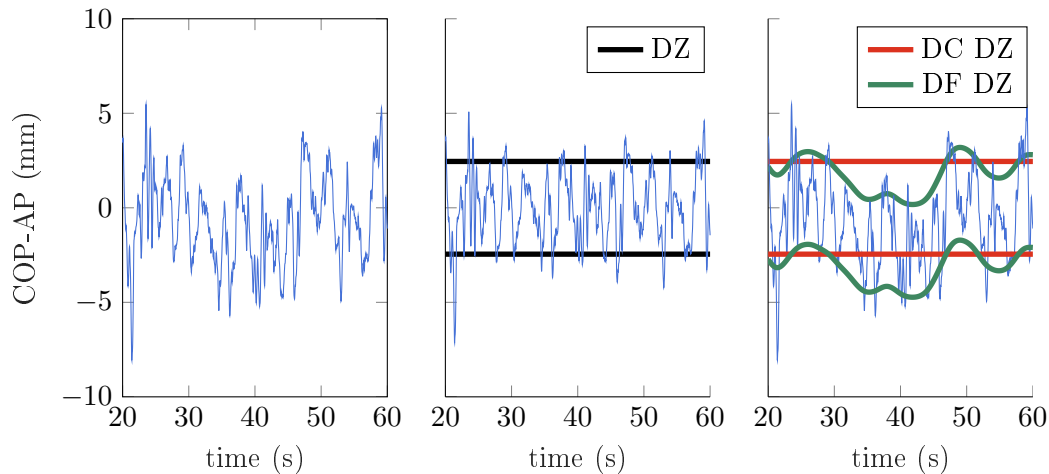


FIGURE 3: Representation of the different steps to compute the Dead-Zone (first 2 plots) : the drift (present in the first plot) is removed and the size of the dead-zone is computed. Representation of how the Dead-Zone would be for the DC and DF biofeedback are in the third plot. This is only for illustration purposes, this is not a trial with Biofeedback so the effect of the Biofeedback cannot be seen. DZ : Dead-zone

### 2.5.1 Drift Constrained biofeedback (DC)

The DC Biofeedback informs the participant if the position of his/her COP exceeds a dead-zone. The DZ informs the participant of the position set-point, the position around which they must minimize sway. The chosen position was the average position of the participant for the first 4s of each trial.

The part of the handle vibrating (anterior or posterior part of the handle) indicated to the participant the position of their COP (anterior or posterior) relative to the dead-zone. Whether providing more information than just an alarm is useful is discussed in the literature. It seems that it is useful, at least during the beginning of the use (Bechly et al., 2013; Dozza et al., 2011). The kind of feedback used is called repulsive, it means that the participant must go in the other direction as the one indicated. For example, when the anterior part of the handle is vibrating, the participant must lean backwards, in the posterior direction. The repulsive feedback was chosen over the attractive kind for

several reasons. First, [Kinnaird et al. \(2016\)](#) showed that repulsive cues allowed better performances (at least when the amount of time of use is limited). Secondly, we are studying the use of the Biofeedback combined with Grounded Grip. When touching, touch cues are providing information about the movement of the body. When the body is going forward, the Center of Pressure of the hand is also going in the same direction (see Chapter 3). Providing repulsive cues seemed more intuitive as they would be evolve in the same direction as touch cues.

The stimulation was a vibration of constant intensity through the experiment but frequency-modulated by the temporal rate of change of the COP displacements. The frequency of the vibration indicated the amplitude of the COP displacements. For example, if the participant is leaning forward out of the dead-zone, the front part of the handle will vibrate and the frequency will decrease as the participant is leaning back towards the dead-zone. The choice of frequency-modulation over amplitude-modulation was motivated by the feedback from individuals during preliminary tests. They deemed the frequency-modulation more comfortable. Furthermore, a frequency-modulation can be used to elicit friction-like illusions and might thus require less "decoding" from the participant. [Ballardini et al. \(2020\)](#) show that a vibrotactile biofeedback with a frequency-modulation can be use to reduce sway. The frequency gain was chosen so the minimal frequency would be perceivable and comfortable while affording a perceivable and comfortable increase. This was adjusted with input of various individuals during preliminary tests.

A summary of what is happening during the balance trials is presented in the pseudo-code in Algorithm 1 with  $A$  representing the constant intensity of the vibration and  $K(t) = 50 * |COP(t)|$  the frequency modulation.

---

**Algorithm 1:** Biofeedback DC

---

```

if  $COP(t) > Threshold$  then
     $Vib_{ant} \leftarrow A \sin(2\pi Kt)$  ;           // anterior part vibrating
     $Vib_{post} \leftarrow 0$  ;
else if  $COP(t) < -Threshold$  then
     $Vib_{ant} \leftarrow 0$ ;
     $Vib_{post} \leftarrow A \sin(2\pi Kt)$  ;       // posterior part vibrating
else
     $Vib_{ant} \leftarrow 0$  ;
     $Vib_{post} \leftarrow 0$  ;

```

---

Figure 4 shows when the biofeedback is activated for both actuators (anterior and posterior) as a function of the position of the COP relative to the Dead-Zone symbolized by the green Thresholds.

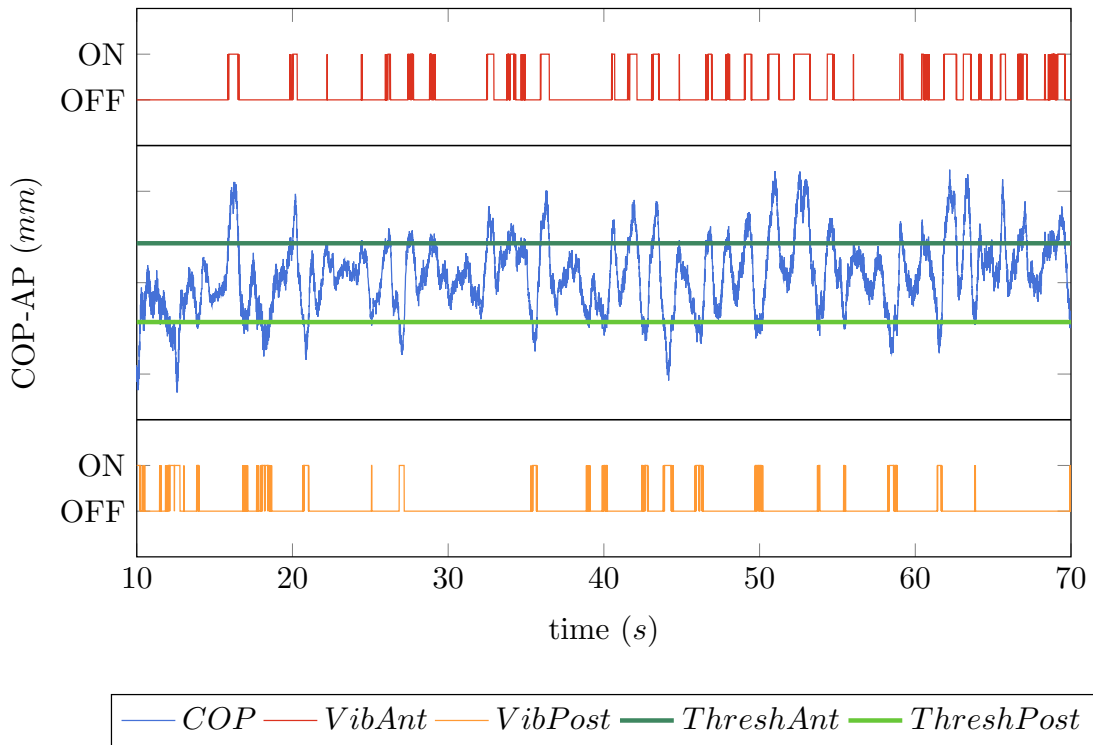


FIGURE 4: Biofeedback DC : Activation of the actuators (anterior and posterior) as a function of the position of the COP relative to the Dead-Zone. This graph shows the activation of the actuators. The signal delivered was a sinusoid of modulated frequency that is not represented for illustration purposes.

### 2.5.2 Drift Free Biofeedback (DF)

Contrary to the DC Biofeedback, the position of the DZ is not imposed. Participants can drift while swaying as little as possible, the drift is not constrained by the biofeedback device. The COP position was band-pass filtered with a butterworth filter of 0.1 and 5Hz cut-off frequency. This Biofeedback acts like an alarm, informing the participant that they are swaying too much, that their sway is superior to the DZ size.

The Biofeedback is designed to inform the participant that he/she is out of the dead-zone. Providing an anterior or posterior information specifically would possible influence participants drift-wise. To avoid this bias, both parts of the handle were vibrating simultaneously outside of the dead-zone with a fixed frequency.

The stimulation was thus a vibration of constant intensity and frequency ( $120Hz$ ) through the experiment.

A summary of what is happening during the balance trials is presented in the pseudo-code in Algorithm 2 with  $A$  representing the constant intensity of the vibration.

---

**Algorithm 2:** Biofeedback DF
 

---

```

if  $|COP(t)| > Threshold$  then
     $Vib_{ant} \leftarrow A \sin(2\pi 120t)$  ;           // anterior part vibrating
     $Vib_{post} \leftarrow A \sin(2\pi 120t)$  ;       // posterior part vibrating
else
     $Vib_{ant} \leftarrow 0$  ;
     $Vib_{post} \leftarrow 0$  ;
  
```

---

Figure 5 shows when the Feedback is activated as a function of the position of the COP relative to the Dead-Zone symbolized by the black Thresholds. Only one activation of the actuators curve is plotted as both actuators vibrate simultaneously.

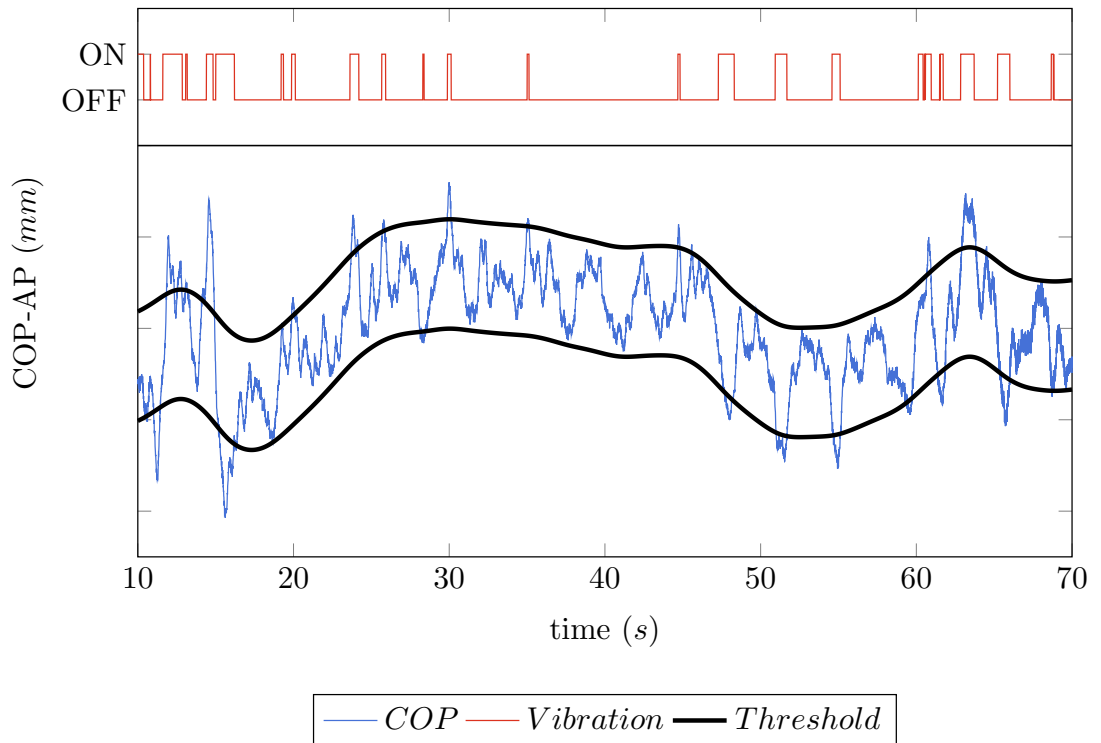


FIGURE 5: Biofeedback DF : Activation of the actuators (anterior and posterior) as a function of the position of the COP relative to the Dead-Zone. This graph shows the activation of the actuators. The signal delivered was a sinusoid of constant frequency that is not represented for illustration purposes.

## 2.6 Experimental Protocol

The experimental protocol was designed to test the effect of two Biofeedbacks (Biofeedback DC and Biofeedback DF) in different gripping conditions (Air Grip and Grounded Grip).

A misunderstanding of the biofeedback could lead to various effects including an absence of effect but not only. To rule out this hypothesis, the intelligibility of the biofeedback must be tested. This was done in a preliminary experiment. The preliminary experiment is detailed in the appendix [C](#).

The entire experiment consisted in several steps :

- Preliminary experiment
- Calibration of the biofeedback : Computation of the two Dead-Zones
- Main experiment
  - Part 1 : Familiarization and sway reduction trials (DC or DF)
  - Part 2 : Familiarization and sway reduction trials (DF or DC)

The main experiment was divided into 2 parts based on the biofeedback delivered. to avoid confusion.

The overall experiment took less than 2 hours.

The participants were asked to stand bare-feet with the feet width-hip apart, on the force platform and to hold the handle in their dominant hand and to reduce their sway as much as possible, with eyes closed. For the Grounded Grip trials, participants were asked to hold only lightly the handle as not to apply a force greater than  $1N$ . An auditory alarm informed them if they applied more than  $1N$ . Participants were explained that if the alarm sounded, the trials would not be repeated or stopped but that they needed to apply less force on the handle whether it is less pushing or less pulling on the handle. Participants experimented with the force level and the alarm before the trials. This was done so they would not be startled and that they would know the acceptable amount of force before the trial. The experimenter ensured that the handle was always held in the same way to prevent a holding bias.

### 2.6.1 Calibration of the Biofeedback

As explained in the section [2.5](#), the thresholds of the DZ of each participant were computed for Air Grip and Grounded Grip independently. Each participant had one Grounded Grip DZ and one Air Grip DZ used for both Biofeedbacks.

The threshold was computed using the COP data of one trial of 70s for each Gripping condition : One trial for Air Grip and one trial for Grounded Grip. These trials were without Biofeedback. As previously explained, the threshold is a measure of the amplitude of COP oscillations without the drift.

### 2.6.2 Main Experiment

The main experiment was divided in two parts based on the biofeedback. The first biofeedback presented was randomly chosen. Presenting the two biofeedbacks in a randomized order in the same part would likely be confusing for the participant.

**Experimental conditions** The influence of Grip and of the Biofeedback was tested. The Grip factor was divided into two levels : Air Grip (AG) and Grounded Grip (GG) and the Biofeedback factor into three levels : No Biofeedback (NF), Biofeedback DC (DC) and Biofeedback DF (DF). All six conditions (Grip x Biofeedback) are summarized in the Table 1.

		Grip	
		Air Grip	Grounded Grip
Biofeedback	No Biofeedback	AG-NF	GG-NF
	Biofeedback DC	AG-DC	GG-DC
	Biofeedback DF	AG-DF	GG-DF

TABLE 1: Experimental conditions

As stated before, the trials were divided into 2 parts based on the biofeedback. Inside each part, each trial with biofeedback was repeated 3 times in a pseudo-randomized order. The trials without feedback (AG-NF and GG-NF), repeated 3 times each were distributed inside the two parts.

After each trial, participants were asked to rate how focused they were from 1 to 5. They were not asked about their performance. The rating scale is the following :

1. almost always forgot to minimize
2. forgot more than half of the time
3. focused most of the time but forgot or eased off repeatedly
4. A few slips or easing offs but rare
5. almost always focused

Every trial with a grade below 3 was repeated without notifying the participant. No more than 2 trials were repeated as participants would loose their focus even more.

**Familiarisation with the biofeedback device** The participants were given explanations concerning the two Biofeedbacks. For both parts of the experiment, participants were explained that they needed to minimize their sway whether there was a Biofeedback and whether the handle was attached or not. Participants were also explained that they needed to minimize as much as possible even within the Dead-Zone.

1. For Biofeedback DC : Participants were explained that
  - there would be a Dead-Zone ;
  - This Dead-Zone would indicate the position around which they needed to minimize their sway ;
  - a vibration of the anterior part of the handle indicated that they were "in front" of the Dead-zone and that a vibration of the posterior part indicated that they were "behind" the Dead-Zone.
2. For Biofeedback DF : Participants were explained that
  - there would be a Dead-Zone ;
  - both parts of the handle would vibrate if they were moving too much ;
  - the position around which they are minimizing is not imposed but they should not explore the space voluntarily.

After the explanations, participants were given as much time as needed to get familiar with the biofeedback device. The participants were instructed to move forward and backward to experience the vibrations in the two directions to ensure that the participant associated the position of the vibration with the movement of his/her body and that they felt the dead-zone position for the Biofeedback DC. Participants were told they could voluntarily change positions in the familiarization part to better understand the Biofeedback DF.

Participants were reminded their task before each trial : the minimization of sway.

## 2.7 Data Collection and Analysis of the Main experiment

### 2.7.1 Data Collection

Kinematics of the body (COM, shoulder, hip and ankle) were recorded using the Optitrack system with a sampling frequency of  $200Hz$ . The data of the force platform used to monitor the COP of the participant for the biofeedback were recorded for further analysis of the COP trajectories. The COP was computed as explained by the equation 2.2 in chapter 2. The platform data was recorded with a sampling frequency of a  $4kHz$ .

The biofeedback output (input of the vibrators) were recorded as well as the data of the force sensor with a sampling frequency of a  $4kHz$ .

### 2.7.2 Analysis

*R* software was used for the statistical Analysis. For each statistical procedure, The Shapiro Wilk test was used to check the normality of the collected data. Log ( $\log_{10}$  and *logit*) transformations were used for non normal residuals. Post-hoc t-tests were used if significance was reached. The threshold for statistical significance was set to  $p = .05$ . P-values were adjusted using the Bonferroni multiple testing correction method. The Greenhouse-Geiser corrections were used as Biofeedback factor is three-fold.

**Sway Reduction Performance** COM RMS Velocity in the time domain was used as the main performance indicator of sway reduction. The choice of this index is explained in chapter 4. As in Chapter 4, the COM signals were low-pass filtered with a butterworth lowpass filter of  $1.5Hz$  cut-off frequency.

A 2-way (2x3) repeated measures ANOVA with the Biofeedback and Grip as factors were used to study the effect of the Biofeedback and the effect of Grip and the interaction between Grip and Biofeedback on sway minimization.

**Sway displacement amplitude and Correcting Activity** The COP Power was calculated on several frequency bands as well as the entire frequency range :

- the entire frequency range  $[0.04 - 1.5Hz]$  ;
- the low frequency band  $[0.04 - 0.5Hz]$
- the drift band  $[0.04 - 0.1Hz]$  ;
- the high frequency band  $[0.5 - 1.5Hz]$ .

Further explanation can be found in section 2.

A 2-way (2x3) repeated measures ANOVA with the Biofeedback and Grip as factors were used to study the effect of the Biofeedback and the effect of Grip and their interaction on COP Power for a sway-minimization task on the different frequency bands.

**Modification of the Amount of Movement around the Hip Joint** A modification of the amount of movement around the hip joint can be identified by analysing the correlation of the hip and shoulder positions (using a small-angle approximation).

- positive correlation and "close" to 1 : predominant displacement of the shoulder and hip in the same direction
- negative correlation and "close" to -1 : predominant displacement of the shoulder and hip in opposed direction



— a modification from 1 and -1 toward -1 indicates an increased movement around the hip joint

A 2-way (2x3) repeated measures ANOVA with the Biofeedback and Grip as factors were used to study the effect of the Biofeedback and the effect of Grip and their interaction on hip and shoulder correlation.

**Amount of Feedback** The amount of vibration the participants received depending on the Biofeedback and Grip conditions was studied. This index reflects the time spent inside the Dead-zone as well as the amount of information given to participants.

A 2-way (2x2) repeated measures ANOVA with the Biofeedback and Grip as factors was used. The Biofeedback factor was reduced to two levels : Biofeedback DC and Biofeedback DF.

### 3 Results

The results of the preliminary experiment detailed in the Appendix C show that participants identified almost perfectly the part that was vibrating. An incorrect identification of the part vibrating is thus not a likely explanation for surprising effects of the Biofeedback.

#### 3.1 Sway Minimization Performance

RMS COM Velocity results are shown in Figure 6A. The mean and standard deviations are in Table 6B.

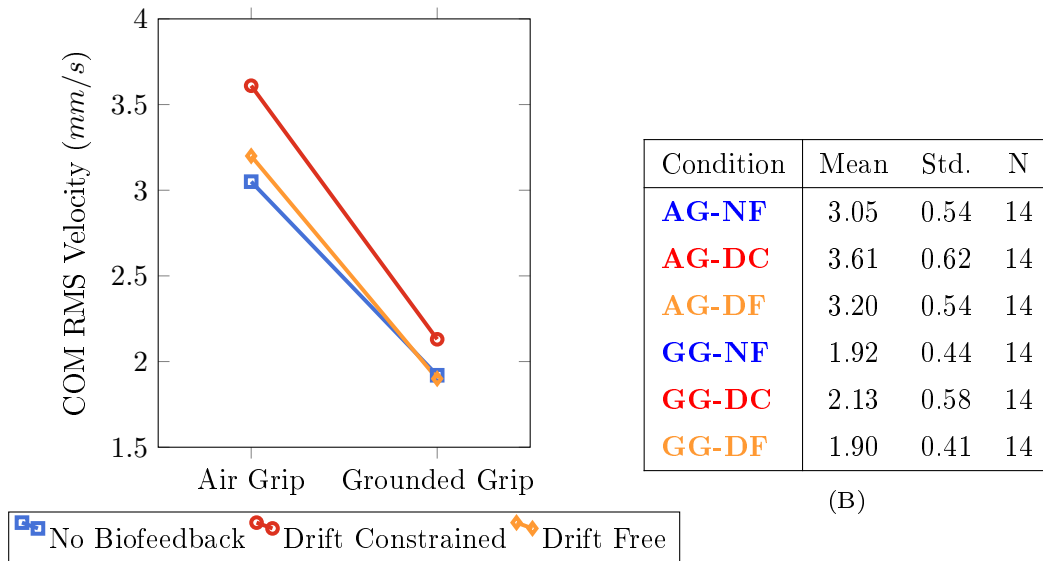


FIGURE 6: RMS COM Velocity ( $mm/s$ ) for all conditions for all 14 participants in (A) with the descriptive Statistics (Mean and Standard deviation) associated in (B) with **AG** : Air Grip, **GG** : Grounded Grip, **NF** : No Biofeedback, **DC** : Biofeedback Drift Constrained, **DF** : Biofeedback Drift Free.

##### 3.1.1 Observations

We can see from Figure 6A and Table 6B that Grounded Grip mean values are inferior to Air Grip for all feedbacks. Furthermore, No Biofeedback and Biofeedback DF are very similar for both Grounded Grip and Air Grip where as Biofeedback DC mean values are greater than No Biofeedback and Biofeedback DF for both Air Grip and Grounded Grip. The Velocity of the COM is increased with the Biofeedback DC while not modified by the Feedabck DF.

### 3.1.2 Statistical Analysis

A two-way repeated measures ANOVA was performed to evaluate the effects of Biofeedback and Grip on RMS COM Velocity. The statistical analysis showing a effect of Biofeedback and of Grip. P-values of the pairwise comparisons are presented in Table 2.

### 3.1.3 Summary

The RMS Velocity of the COM was reduced with Grounded Grip compared to Air Grip for all Biofeedbacks, No Biofeedback included (**GG < AG**). However, the RMS Velocity of the COM was significantly increased in mean with the Biofeedback DC compared to No Biofeedback for Air Grip (**AG-DC > AG-NF**). This was the only significant difference between the different Biofeedbacks may they be for Air Grip or Grounded Grip.

	Pairs	P-value
Biofeedback	<b>AG-NF</b> vs <b>AG-DC</b>	<b><math>p &lt; .001</math></b> ↗
	<b>AG-NF</b> vs <b>AG-DF</b>	$p = .75$
	<b>AG-DC</b> vs <b>AG-DF</b>	$p = .1$
	<b>GG-NF</b> vs <b>GG-DC</b>	$p = .057$
	<b>GG-NF</b> vs <b>GG-DF</b>	$p > .99$
	<b>GG-DC</b> vs <b>GG-DF</b>	$p = .098$
Grip	<b>AG-NF</b> vs <b>GG-NF</b>	<b><math>p &lt; .001</math></b> ↘
	<b>AG-DC</b> vs <b>GG-DC</b>	<b><math>p &lt; .001</math></b> ↘
	<b>AG-DF</b> vs <b>GG-DF</b>	<b><math>p &lt; .001</math></b> ↘

TABLE 2: P-values of the post-hoc t-test pairwise comparisons of the RMS COM Velocity. Significant comparisons are in bold. **Arrows indicate the direction of the change between the first and second part of the pair.**

## 3.2 COP : A look into Sway Amplitude and Correcting Activity

Unlike in Chapter 4, the PSD plot for all participants pulled together was not shown as plots from one participant to another are very different. The plots per participant are shown in appendix C.

The statistical analysis of the COP Power is divided into several parts based on frequency bands that are the following : Entire Frequency range :  $[0.04 - 1.5Hz]$  ; Low

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Frequency band :  $[0.04 - 0.5Hz]$  ; Drift band :  $[0.04 - 0.1Hz]$  and High Frequency band :  $[0.5 - 1.5Hz]$ .

### 3.2.1 COP Power on the Entire Frequency Range

Mean COP Power over the entire frequency range ( $[0.04 - 1.5Hz]$ ) for all participants is presented in Figure 7A. The mean and standard deviations are in Table 7B.

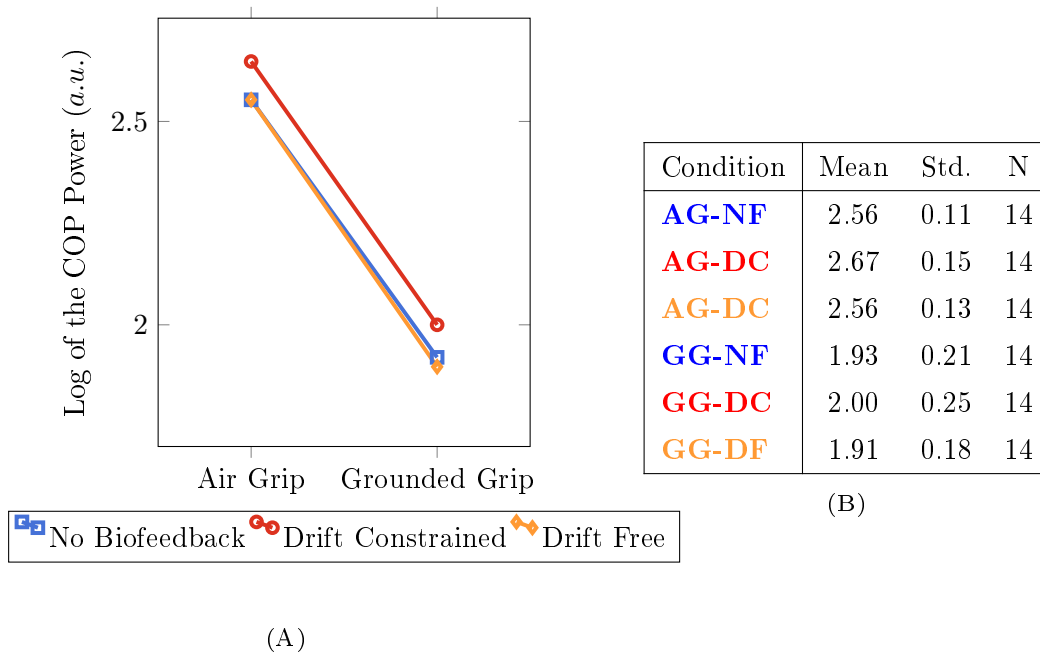


FIGURE 7: COP Power for all conditions for all participants in log scale in (A) with the descriptive Statistics (Mean and Standard deviation) after log-transformation for the entire frequency range for N participants in (B) with **AG : Air Grip**, **GG : Grounded Grip**, **NF : No Biofeedback**, **DC : Biofeedback DC**, **DF : Biofeedback DF**.

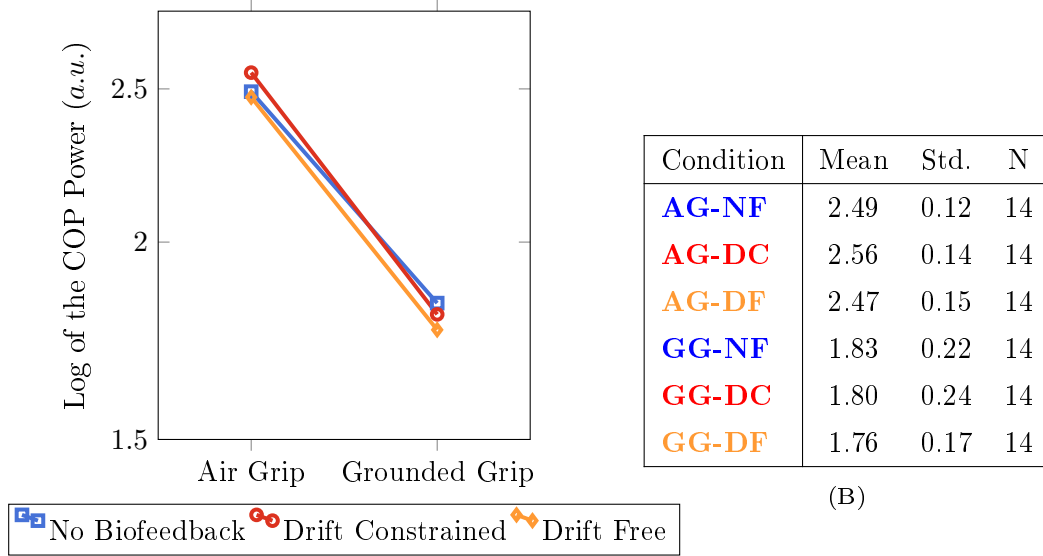
**Observations :** We can see from Figure 7A and values in Table 7B that COP Power is reduced with Grounded Grip compared to Air Grip for all Biofeedbacks. COP Power for the No Biofeedback and Biofeedback DF seem identical for Air Grip and Grounded Grip while Biofeedback DC is different. Mean Values for the Biofeedback DC seem greater than No Biofeedback and Biofeedback DF for Air Grip and Grounded Grip.

**Statistical Analysis :** A two-way repeated measures ANOVA was performed to evaluate the effects of Biofeedback and Grip on COP Power for the entire frequency range. The statistical analysis revealed an effect of Biofeedback and of Grip. P-values of the pairwise comparisons are presented in Table 3.

**Summary :** The analysis of the COP Power for the entire frequency band shows that the COP Power is significantly reduced with Grounded Grip (**GG COP Power < AG COP Power**) but that it is significantly increased with the Biofeedback DC compared to No Biofeedback without Grip (**AG-DC > AG-NF**).

### 3.2.2 Center of Pressure Power on the Low Frequency Band

Mean COP Power over the low frequency band ( $[0.04 - 0.5Hz]$ ) for all participants is presented in Figure 8A. The mean and standard deviations are in Table 8B.



(A)

FIGURE 8: COP Power for the low frequency band for all participants in log scale in (A) with the descriptive Statistics (Mean and Standard deviation) after log-transformation for the low frequency band for N participants in (B) with **AG** : Air Grip, **GG** : Grounded Grip, **NF** : No Biofeedback, **DC** : Biofeedback DC, **DF** : Biofeedback DF.

**Observations :** We can see from figure 8A that COP Power is reduced with Grounded Grip compared to Air Grip for all Biofeedbacks. COP Power for the No Biofeedback, Biofeedback DF and Biofeedback DC seem identical for Air Grip and Grounded Grip.

**Statistical Analysis :** A two-way repeated measures ANOVA was performed to evaluate the effects of Biofeedback and Grip on COP Power on the low frequency band  $0.04 - 0.5Hz$ . The analysis reveals only a main effect of Grip. P-values of the pairwise comparisons are presented in Table 3.

**Summary :** The analysis of the COP Power for the low frequency band shows that the COP Power is significantly reduced with Grounded Grip (**GG COP Power** < **AG COP Power**) but that the Biofeedback does not have an effect on COP Power.

### 3.2.3 Center of Pressure Power on the Drift Band

Mean COP Power over the drift band ( $[0.04 - 0.1Hz]$ ) for all participants is presented in Figure 9A. The mean and standard deviations are in Table 9B.

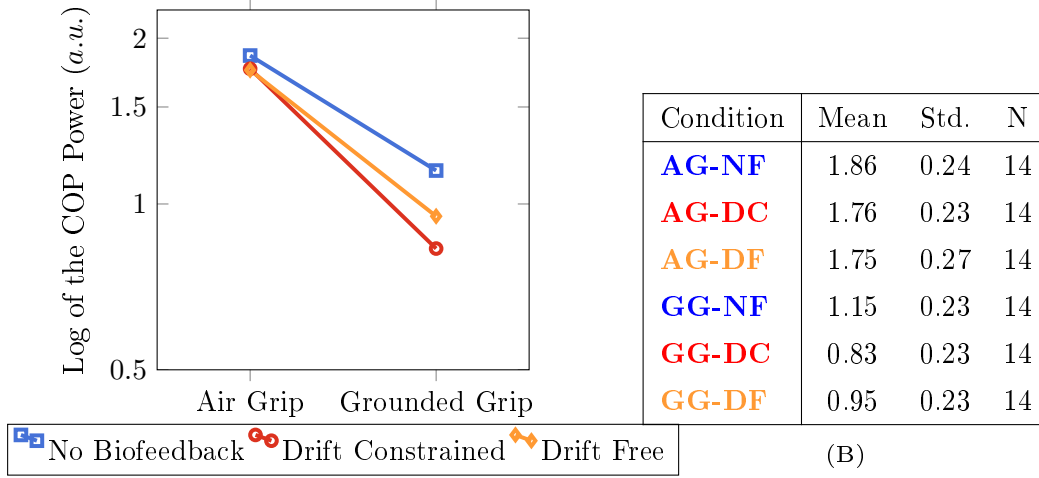


FIGURE 9: COP Power for the drift band for all participants in log scale in (A) with the descriptive Statistics (Mean and Standard deviation) after log-transformation for the drift band for N participants in (B) with **AG : Air Grip**, **GG : Grounded Grip**, **NF : No Biofeedback**, **DC : Biofeedback DC**, **DF : Biofeedback DF**.

**Observations :** We can see from Figure 9A that COP Power is reduced with Grounded Grip compared to Air Grip for all Biofeedbacks. For Air Grip, both Biofeedback DC and DF have slightly lower mean values than No Biofeedback. For Grounded Grip, both Biofeedback DC and DF have lower mean values than No Biofeedback, however, the difference is much greater than for Air Grip. Biofeedback DC presents a greater reduction than Biofeedback DF compared to No Biofeedback for Grounded Grip.

**Statistical Analysis :** A two-way repeated measures ANOVA was performed to evaluate the effects of Biofeedback and Grip on the COP power on the frequency band corresponding to the drift ( $[0.04 - 0.1Hz]$ ). The analysis reveals an effect of Grip and Biofeedback. P-values of the pairwise comparisons are presented in Table 3.

**Summary :** The analysis of the COP Power for drift band shows that the COP Power is reduced with Grounded Grip (**GG COP Power < AG COP Power**) and that COP Power is reduced with the Biofeedback DC and DF for Grounded Grip (**GG-DC < GG-NF** and **GG-DF < GG-NF**).

### 3.2.4 Center of Pressure Power on the High Frequency Band

Mean COP Power over the high frequency band ( $[0.5 - 1.5Hz]$ ) for all participants is presented in Figure 10A. The mean and standard deviations are in Table 10B.

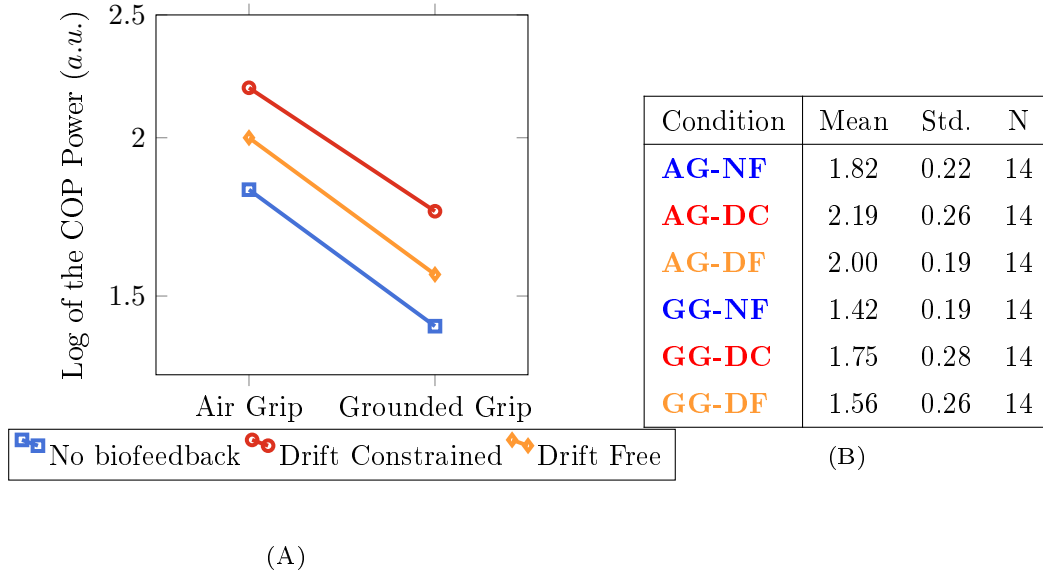


FIGURE 10: COP Power for the high frequency band for all participants in log scale in (A) with the descriptive Statistics (Mean and Standard deviation) after log-transformation for the high frequency band for N participants in (B) with **AG** : Air Grip, **GG** : Grounded Grip, **NF** : No Biofeedback, **DC** : Biofeedback DC, **DF** : Biofeedback DF.

**Observations :** We can see from figure 10A that COP Power is reduced with Grounded Grip compared to Air Grip for all Biofeedbacks. Both Biofeedback DC and DF present greater mean values than No Biofeedback for both Air Grip and Grounded Grip. Biofeedback DC presents greater mean values than both Biofeedback DF and No Biofeedback. The slopes seem parallel supposing an absence of interaction of Grip and Biofeedback.

**Statistical Analysis :** A two-way repeated measures ANOVA was performed to evaluate the effects of Biofeedback and Grip on the COP Power for the high frequency band ( $[0.5 - 1.5Hz]$ ). The statistical analysis shows an effect of Biofeedback and Grip. P-values of the pairwise comparisons are presented in Table 3

**Summary :** The analysis of the COP Power for high frequency band shows that the COP Power is reduced with Grounded Grip (**GG COP Power** < **AG COP Power**). The effect of the Biofeedback is different from one Biofeedback to the other and depending on the Grip condition even if no interaction was found. Both Biofeedback DC and DF show greater COP Power than No Biofeedback for Air Grip (**AG-DC** > **AG-NF** and



**AG-DF** > **AG-NF**). However, the Biofeedback DC shows greater COP Power than Biofeedback DF for Air Grip (**AG-DF** < **AG-DC**). For Grounded Grip, only the Biofeedback DC was different from the No Biofeedback (**GG-DC** > **GG-NF**). The Biofeedback DF was not significantly different than No Biofeedback however a tendency can be observed on the Figure 10A and it was not different from Biofeedback DC which is different from No Biofeedback .

### 3.2.5 Summary of the Analysis on the Different Frequency Bands

The trajectory of the COP represents the time-varying forces generated by the muscles in the stabilization of the body. The low frequencies, below  $0.5Hz$  are considered to represent body sway.

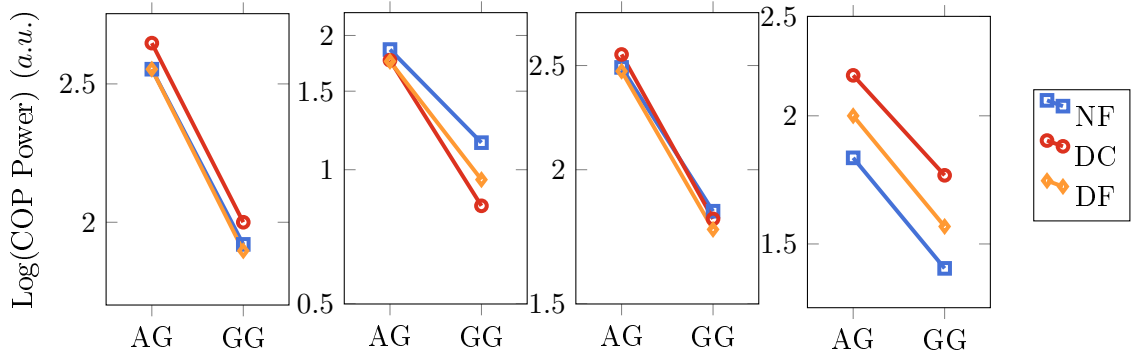
We decomposed the analysis of COP Power based on this assumption :

- Entire Frequency range ( $[0.04 - 1.5Hz]$ );
- Low frequency band ( $[0.04 - 0.5Hz]$ ) with a focus on
- Drift band ( $[0.04 - 0.1Hz]$ ) and
- High Frequency band ( $[0.5 - 1.5Hz]$ ).

We found that while Grip had an effect regardless of the frequency band (decrease of COP Power with Grounded Grip **GG** < **AG**), Biofeedback had different effects depending on the frequency band.

We can summarize :

- COP Power was reduced with Grounded Grip for the different frequency bands and the entire range (**GG** < **AG**);
- COP Power on the entire frequency range is not modified by the presence except with Air Grip and the biofeedback DC (**Entire range : Air Grip : Biofeedbacks DC** > **No Biofeedback**);
- Low Frequency COP Power is not modified by the presence of Biofeedbacks (**Low Frequency : No Biofeedback**  $\approx$  **Biofeedbacks DC and DF**);
- For Air Grip : The Drift is not modified in presence of Biofeedbacks (**Air Grip Drift : No Biofeedback**  $\approx$  **Biofeedbacks DC and DF**). The high frequencies are increased with both biofeedbacks but to a greater extent with the Biofeedback DC (**Air Grip High Frequency : DC** > **NF** and **DF** > **NF** and **DC** > **DF**).
- For Grounded Grip : The Drift is reduced (**Grounded Grip Drift : DC** < **NF** and **DF** < **NF**)The high frequencies are increased with the biofeedback DC only (**Grounded Grip High Frequency : DC** > **NF** and **DF**  $\approx$  **NF**).



(A) Entire range

(B) Drift

(C) Low Freq

(D) High Freq

FIGURE 11: COP Power for the (A) entire frequency range (B) drift, (B) low frequency and (D) high frequency bands for all conditions for all participants. **AG : Air Grip**; **GG : Grounded Grip**; **NF : No Biofeedback**; **DC : Drift Constrained**; **DF : Drift Free**.

	Pairs	All Freq.	Low Freq	Drift	High Freq.
Biofeedback	<b>AG-NF</b> vs <b>AG-DC</b>	$p = .002$ ↗	NME	$p = .441$	$p < .001$ ↗
	<b>AG-NF</b> vs <b>AG-DF</b>	$p > .99$	NME	$p = .66$	$p = .015$ ↗
	<b>AG-DC</b> vs <b>AG-DF</b>	$p = .148$	NME	$p > .99$	$p = .019$ ↘
	<b>GG-NF</b> vs <b>GG-DC</b>	$p = .522$	NME	$p = .01$ ↘	$p < .001$ ↗
	<b>GG-NF</b> vs <b>GG-DF</b>	$p > .99$	NME	$p = .018$ ↘	$p = .2$
	<b>GG-DC</b> vs <b>GG-DF</b>	$p = .363$	NME	$p = .558$	$p = .069$
Grip	<b>AG-NF</b> vs <b>GG-NF</b>	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘
	<b>AG-DC</b> vs <b>GG-DC</b>	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘
	<b>AG-DF</b> vs <b>GG-DF</b>	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘	$p < .001$ ↘

TABLE 3: P-values of the post-hoc t-test pairwise comparisons for the three frequency bands and the entire frequency range. **AG : Air Grip**, **GG : Grounded Grip**, **NF : No Biofeedback**, **DC : Biofeedback DC**, **DF : Biofeedback DF**. Significant differences are in bold. NME : No Main Effect. **Arrows indicate the direction of the change between the first and second part of the pair.**

### 3.3 Modification of the Amount of Movement around the Hip Joint

The correlation of hip and shoulder positions for thirteen out of fourteen participants is shown in Figure 12B after logit transformation. For clarity purposes, the correlations before transformation are shown in Figure 12A. One participant was excluded as too many data points were missing from occlusion of optical markers. For three participants out of thirteen, two correlation values instead of three were used to compute the mean per participant due to a lack of data points. As the correlation values were naturally between 0 and 1, the data was log transformed using the *logit* instead of the *log*<sub>10</sub>.

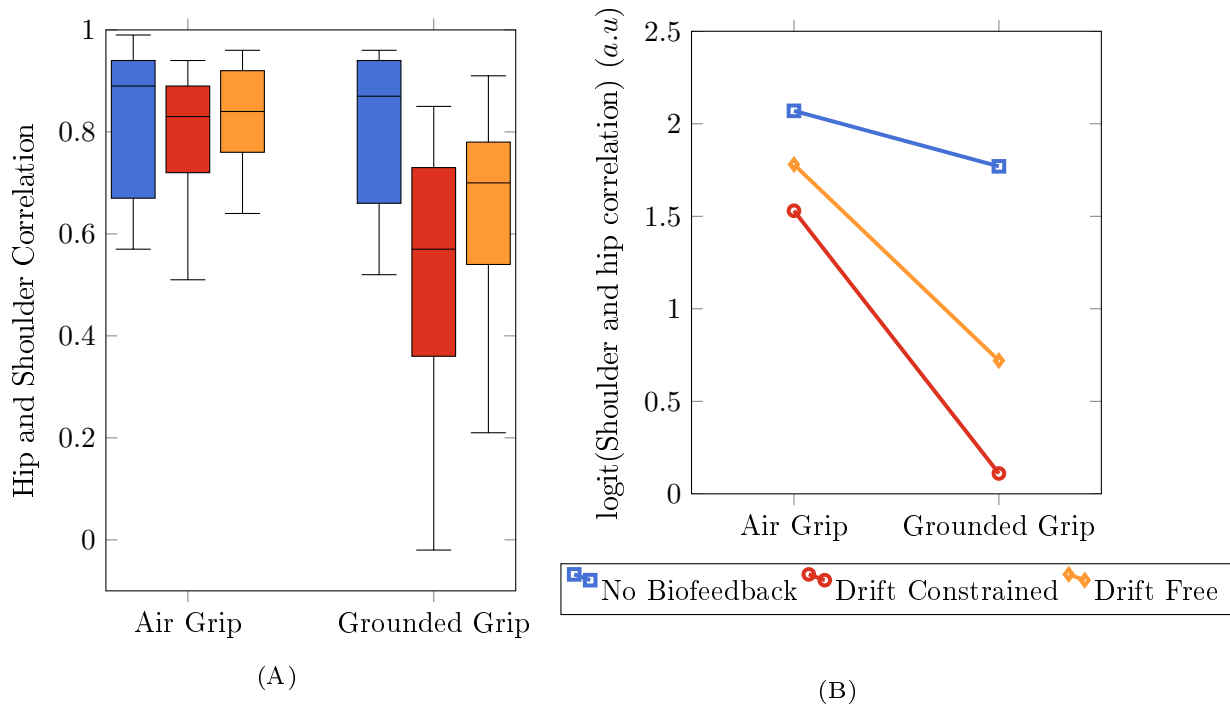


FIGURE 12: Hip and shoulder correlations for 13 out of 14 participants. (A) Boxplot in linear scale and (B) in logit scale with **NF : No Biofeedback**, **DC : Biofeedback DC**, **DF : Biofeedback DF**. The colors of the boxplot are the same than the interaction graph.

**Observations** We can observe in Figure 12B that the correlation coefficient are smaller with Grounded Grip and especially with Biofeedback. The correlation coefficient is close to 0 with Grounded Grip and Biofeedback DC. This suggests that participants increased the amount of movement around the hip joint when they have the Biofeedback and Grounded Grip.

**Statistical Analysis** A two-way repeated measures ANOVA was performed to evaluate the effects of Biofeedback and Grip on the shoulder and hip correlation. The analysis reveals an effect of Biofeedback and Grip.

**Summary** The analysis shows that participants mostly swayed around the ankles in absence of Biofeedback. However, an increase of hip use appears for Grounded Grip in presence of Biofeedback (**hip use : GG-DC > GG-NF ; GG-DF > GG-NF ; GG-DC > AG-DC and GG-DF > AG-DF**).

	Pairs	P-value
Biofeedback	<b>AG-NF</b> vs <b>AG-DC</b>	$p = .243$
	<b>AG-NF</b> vs <b>AG-DF</b>	$p > .99$
	<b>AG-DC</b> vs <b>AG-DF</b>	$p > .99$
	<b>GG-NF</b> vs <b>GG-DC</b>	$p < .001$ ↘
	<b>GG-NF</b> vs <b>GG-DF</b>	$p = .033$ ↘
	<b>GG-DC</b> vs <b>GG-DF</b>	$p = .369$
Grip	<b>AG-NF</b> vs <b>GG-NF</b>	$p = .466$
	<b>AG-DC</b> vs <b>GG-DC</b>	$p = .004$ ↘
	<b>AG-DF</b> vs <b>GG-DF</b>	$p = .002$ ↘

(A)

Condition	Mean	Std.	N
<b>AG-NF</b>	2.07	1.2	13
<b>AG-DC</b>	1.53	0.72	13
<b>AG-DF</b>	1.78	0.78	13
<b>GG-NF</b>	1.77	1.09	13
<b>GG-DC</b>	0.11	1.46	13
<b>GG-DF</b>	0.72	1.0	13

(B)

FIGURE 13: (A) P-values of the post-hoc t-test pairwise comparisons of the correlation of hip and shoulder correlations. Significant comparisons are in bold. **Arrows indicate the direction of the change between the first and second part of the pair.** (B) Descriptive Statistics (Mean and Standard deviation) after logit-transformation for N participants in (B) with **AG : Air Grip, GG : Grounded Grip, NF : No Biofeedback, DC : Biofeedback DC, DF : Biofeedback DF.**

### 3.4 Amount of Feedback Received by the Participants

The amount of vibration received by the fourteen participants is shown in Figure 14A. The data was log-transformed ( $\log_{10}$ ). Only Biofeedback DC and DF were used and not the No Biofeedback as we are comparing the amount of feedback received.

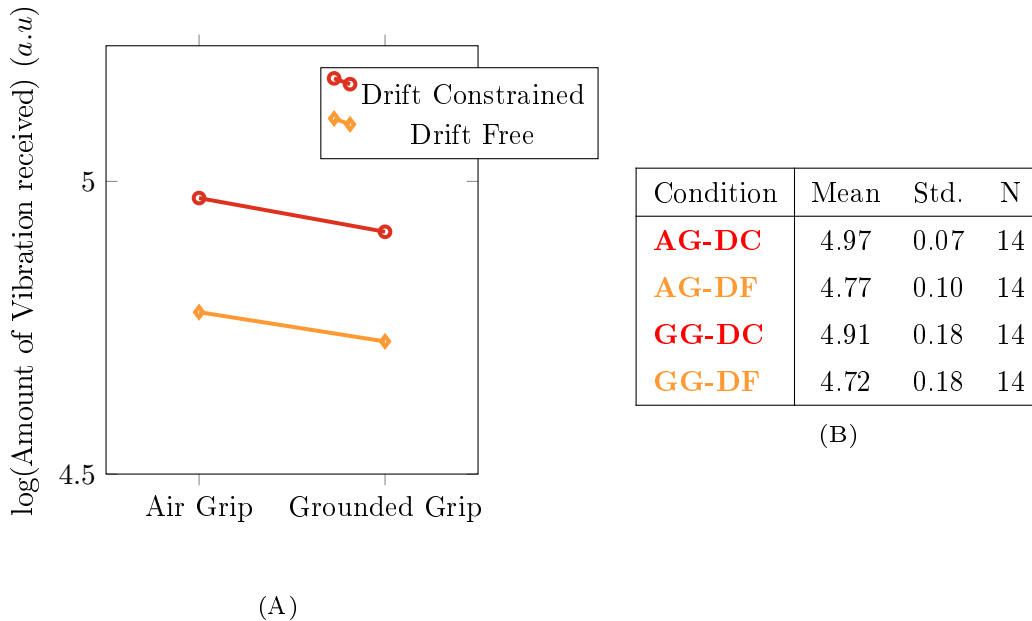


FIGURE 14: Amount of Vibration received by the 14 participants in log scale in (A) with the descriptive Statistics (Mean and Standard deviation) after log-transformation for N participants in (B) with **AG : Air Grip**, **GG : Grounded Grip**, **DC : Biofeedback DC**, **DF : Biofeedback DF**.

**Observations** We can observe in Figure 14A that the mean amount of vibration received by the participants is greater with the Biofeedback DC than the Biofeedback DF. The amount does not seem to be impacted by Grip as the AG-GG lines seem parallel and almost flat.

**Statistical Analysis** A two-way rm ANOVA was performed to evaluate the effects of Biofeedback and Grip on the amount of vibration received by the participant. The analysis reveals an effect of Biofeedback.

**Summary** The amount of vibration the participants received depends on the biofeedback used but does not depend on the Gripping condition. Participants received significantly more vibrations for the Biofeedback DC (**DC > DF**).

## 4 Discussion

We question the ability to voluntarily reduce sway using a Vibrotactile Biofeedback device with a Grounded Grip or not. The biofeedback was COP Position-driven using two control modes which are referred as Biofeedback DC (Drift Constrained) and Biofeedback DF (Drift Free).

We hypothesised that :

- Grounded Grip cues could be reweighted by the Biofeedback cues. This would induce a greater reduction of sway with Biofeedback for Grounded Grip than without Grounded Grip.
- The Biofeedback not constraining the drift would promote a more efficient reduction of sway than the one constraining the drift of the participant.

### 4.1 Brief Summary of the Results

**Between Air Grip and Grounded Grip :** COP Power and RMS COM Velocity were reduced with Grounded Grip compared to Air Grip regardless of the Biofeedback. Surprisingly, no increased hip use was found with Grounded Grip without Biofeedback compared to Air Grip without Biofeedback.

**For Air Grip :** In brief, the use of the Biofeedback DC led to an increase of the COM Velocity while the low frequency and drift power of COP oscillations were not modified. The absence of modification (COP Low frequency and Drift Power) and increased Velocity were accompanied by an increase of High Frequency COP Power (Biofeedback DC).

**For Grounded Grip :** In brief, the use of the biofeedbacks DC and DF led to no modification of the COM Velocity. The low frequency power of COP oscillations were not modified but the drift power was decreased with both Biofeedbacks. The decreased drift power was accompanied by an increase of High Frequency COP Power for the Biofeedback DC but not the Biofeedback DF. The use of the Biofeedbacks DF and DC induced an increased use of the hip possibly showing a change of coordination strategy.

### 4.2 Information Availability

While the drift COP Power is reduced with Biofeedback DC and DF for Grounded Grip, it is not modified for Air Grip for the two biofeedbacks. This means that in presence

of Grounded Grip cues, participants swayed less (drift-wise) with the two Biofeedbacks compared to without it. Furthermore, RMS COM Velocity was increased with the Biofeedback DC (for Air Grip) compared to No Biofeedback for Air Grip. The absence of decrease for Air Grip with position-based biofeedback is not in line with other studies. However, many studies use challenging stances like the tandem-romberg ([Alahakone & Senanayake, 2010](#) ; [Bechly et al., 2013](#)) stance or by adding foam ([Dozza et al., 2005](#) ; [Lakhani & Mansfield, 2015](#)) or using disturbances that increase the amount of sway without Biofeedback. This increased sway likely induces an increased amount of already existing sensory information. Others use very short trials like [Alahakone et Senanayake \(2010\)](#) (20s trials). Short trials may be adapted for participants with pathologies but they do not allow an overview of sway patterns given the low frequency content of sway. [Saini et al. \(2019\)](#) studied the use of a biofeedback in presence of Light Touch on the back. The Light Touch provided was different in their experiment as the contact with the participant was in the back and the Light contact was assured by an haptic interface (Phantom robot) likely removing the supra-postural constraint of Light Touch/Grip. They explain that their Light Touch only provided velocity-related information. They found a reduction of the amplitude (standard deviation) of COP oscillations with Light Touch compared to No Touch and a reduction of the amplitude of COP oscillations with Light Touch and Vibrotactile Biofeedback. For the amplitude of the velocity of the COP, they found that Light Touch had an effect compared to No Touch No Biofeedback but that Light Touch with the vibrotactile biofeedback was not different from just Light Touch. These results are in line with ours where a reduction of sway (just the drift in our case) was observed but no reduction of the velocity was observed.

The amount of information necessary to reduce sway needs to be questioned. The dominant hypothesis concerning the use of Biofeedback devices for balance is that the information provided by the Biofeedback is used to re-weight the already existing information provided by the senses ([Sienko et al., 2018](#)). For such a re-weighting to be possible and efficient, there needs to be reliable sensory information from the other senses.

Participants are asked to reduce their sway as much as possible. We showed in [Chapter 4](#) that sway can be voluntarily reduced. This means that even without the biofeedback, sway was reduced compared to a relaxed stance. Furthermore, participants were healthy, feet apart without foam inducing a very small sway of the body. This very reduced sway suggests that, without the biofeedback, they do not have much information about their sway. The greater the sway, the greater the amount of information. Perhaps, the amount of information provided by the cutaneous receptors of the feet and proprioception of the legs is not sufficient to reduce further for Air Grip. Furthermore, when the drift is constrained (Biofeedback DC), the amount of sensory information is reduced as participants cannot explore space to gather information. The exploratory theory, supported

by [Carpenter et al. \(2010\)](#) amongst many others, explains that there is a functional role to sway, the movement of the body is used to gather sensory information. As explain in the State of the Art, an accurate haptic perception is usually teamed with a motor behaviour, sway in our case. We can thus question whether the increase of the Velocity of the COM for the Biofeedback DC compared to the others with Air Grip was only a consequence of an inability to reduce sway or if it was a strategy adopted to augment the sensory information. [R. Fitzpatrick et McCloskey \(1994\)](#) explain that the perception thresholds are smaller with a greater sway velocity.

With Grounded Grip, supplementary sensory cues are provided. These information are provided in the hand, closer to the COM. It is likely that the information provided by Grounded Grip are re-weighted with a greater weight in presence of the biofeedback information. This means that a use of the biofeedback would lead to a reduction of sway. The use of the Grounded Grip cues, provided close to the COM are highlighted by the increase of hip use with the two Biofeedbacks in presence of Grounded Grip. We can hypothesise that if the feedback information was used independently of "native" sensory information (cognitive process without sensory-reweighting), there should not be a difference of hip use between Grounded and Air Grip with the Biofeedbacks.

Finally, Grounded Grip is a supra-postural task, while most participants reported after the experiment that it was not difficult, they also reported that it required a bit of focus. Perhaps, this supra-postural constrained added an external focus. The supra-postural task is not in competition with the task of minimization. It is possible that participants attended a part of their attentional focus to this external task promoting perhaps a more automatic and thus more efficient use of the sensory information. [Wulf et al. \(2001\)](#) amongst others explain that an external focus promotes a decreased conscious interference and a higher degree of automaticity.

### 4.3 Discussion of the two Biofeedbacks with Grounded Grip

The use and influence of the Biofeedbacks will be discussed for Grounded Grip for which a reduction of the drift was observed.

The Drift (COP Power) is reduced for both Biofeedbacks DC and DF compared to No Biofeedback. The Low Frequency COP Power on the other hand was not modified by the use of the biofeedback. The reduction of the drift was accompanied by an increase of high frequency COP Power with the Biofeedback DC (Drift Constrained) compared to No Biofeedback but not with the Biofeedback DF (Drift Free).



The drift is reduced with the Biofeedback DC that constrains the drift but the low frequencies are not. The Biofeedback DC constrains the position of the COP as well the amplitude of the COP oscillations. The absence of modification of the low frequencies is in line with the study of [Danna-Dos-Santos et al. \(2008\)](#) where no significant effect of a visual biofeedback was found for the rambling component ( $< 0.3Hz$  compared to  $< 0.5Hz$  in our study). It is possible that the participants prioritized the reduction of the drift over the reduction of the amplitude of the COP oscillations. The amount of Biofeedback received by the participants suggests that the COP position overshoot the threshold. This was reported by most participants at the end of the experiment. An oscillation of increased amplitude around one position would explain the absence of modification of the Low Frequency COP Power.

The drift COP Power is reduced with the Biofeedback DF, not constraining the drift but the low frequency COP Power is not. The Biofeedback DF is providing information if a certain amplitude is exceeded but no information is provided about the drift. The cutting frequency chosen,  $0.1Hz$  is "artificial" and not flexible. It is likely that participants while trying to reduce their sway using the Biofeedback also reduced the drift. It would be interesting to investigate this as the absence of modification of the low frequencies is not trivial and quite surprising.

The Drift COP Power was reduced with the Biofeedback DC and DF with Grounded Grip compared to without Biofeedback. For the Biofeedback DC, constraining the drift, the high frequency COP Power was increased while it was not with the Biofeedback DF, not constraining the drift. [Goodworth et al. \(2009\)](#) tested the use of different vibrotactile biofeedbacks during perturbed stance. The biofeedbacks were driven with either Position of the trunk, Velocity or a combination of both. They found in line with [Loughlin et al. \(2011\)](#) that while position driven biofeedbacks were more effective in reducing low frequencies ( $< 0.23Hz$ ) than velocity based biofeedbacks, they resulted in an increase of higher frequencies ( $> 0.6Hz$ ) compared to velocity-based biofeedbacks. They found no effect of Biofeedbacks on sway velocity. The position-driven biofeedback can be associated to our Biofeedback DC with imposed position and the Biofeedback DF can be seen as a combination of a position and velocity based Biofeedback. A Velocity based biofeedback, like the Biofeedback DF would constrain less the low frequencies but the threshold of the Biofeedback DF is position related. Our results are in line with the findings of Goodworth et al and the study presented by [Loughlin et al. \(2011\)](#). However, in our case, we found no difference in the reduction of the COP Power for the drift band between the Biofeedback DC and DF. The similar reduction of the drift afforded by the Biofeedback DC and DF can perhaps be explained by the fact that we used the COP position in both cases and not a combination of position and velocity.

How can we explain the difference in terms of high frequency between the Biofeedback DC and DF? There was an increase of the frequency of the correcting activity (increase of high frequency COP Power) with the Biofeedback DC while there was not for the Biofeedback DF. Moreover, the high frequency COP Power was even decreased with Grounded Grip compared to Air Grip. The absence of modification of the low frequency Power with the increase of the high frequency Power for the Biofeedback DC is in line with the results of [Danna-Dos-Santos et al. \(2008\)](#) even if the increase of the high frequencies (trembling) was not significant but only a tendency. The use of both Biofeedbacks DC and DF with Grounded Grip induced a decrease of the drift but the difference in the increase of High Frequency with the Biofeedback DC and not DF suggests that the reduction is less efficient with the Biofeedback DC. This is also suggested by the difference of amount of feedback received, participants received significantly more feedback with the Biofeedback DC than DF for a similar reduction of the drift in the end. Furthermore, the integration of a "native" sensory information in a standing still task does not require an additional increase of high frequency but even a decrease (High Frequency Power is reduced with Grounded Grip compared to Air Grip). The reduction afforded by the Biofeedback DF with no significant change of high frequency COP Power, is thus more similar to the integration of a "native" sensory input. This suggests that the use of the Biofeedback DF is more "ecological" than the Biofeedback DC. [Kilby et al. \(2017\)](#) told their participants to reduce sway with a visual biofeedback regardless of the position on the screen as they considered that it was arguably more natural. By giving the instruction, they probably told their participants to ignore the drift rather than constrain it because they considered it was more natural. This is in line with the hypothesis that not constraining the drift is more ecological than to constrain it. Furthermore, [Danna-Dos-Santos et al](#) explain that the paradigm of the control of the inverted pendulum at one resting angle might not be the best representation of postural control. The non-linearity of the postural system and the observations that individuals do not sway around one angle but a range of angles suggests than an intermittent control ([Asai et al., 2009](#); [Bottaro, Yasutake, Nomura, Casadio, & Morasso, 2008](#)) or a control with a migrating set-point ([Rasouli et al., 2017](#); [Zatsiorsky & Duarte, 2000](#)) might represent better postural control. Constraining the drift might promote a less efficient control because it interferes with the control. Not constraining the drift might be more ecological as it gives leeway for the control to organize itself optimally to answer the demands of the instruction to minimize sway.

#### 4.4 Limitations and Perspectives of our Study

Before concluding, we would like to go over some limitations of our study.

First, we have no measure of the stiffness. We did not use EMG to measure the muscular activity hence we do not have information about the level of co-contraction in the different conditions. Most participants reported that they had tried to stiffen to move less but that they had stopped rather quickly as it was efficient for only a very short while and ended up being exhausting and inefficient as the same time. The inefficiency reported is in line with the fact that upright stance cannot be stabilized by stiffness alone (Morasso & Schieppati, 1999). Dozza et al. (2005) report no significant increase of co-contraction but a tendency. Contrary to our study, they used the acceleration of the trunk to drive the biofeedback and not the position.

All participants reported that minimizing using the Biofeedback or without it required them to focus a lot. It would be interesting to add a cognitive and non-perceptual task to differentiate the two biofeedbacks as individuals rarely only stand. It is possible that the Biofeedback DF by constraining less is promoting a more automatic control thus requiring less attentional demands. Krecisz et Kuczyński (2018) found that the use of a visual biofeedback was attention demanding.

All participants were healthy and young without any balance deficits. The sway of participants minimizing, in absence of biofeedback was already quite small. It might be relevant to study the use of the two Biofeedbacks on foam as foam alters the use of proprioception and touch from the feet (cutaneous receptors of the feet). The use of foam would make the task more challenging but would increase sway providing more information at the same time. Furthermore, it was not quantified but all participants but one reported that their breathing made the task even more challenging and most resorted to using apnoea, on accounts of the reports. If participants had been in another stance leading to greater sway, it is possible that breathing would have been less of an issue. The fact that participants felt they could not breath normally or had to voluntary control it is problematic because it is not comfortable and that it possibly hindered their performance.

We think that our study could benefit from the use of other metrics such as the sample entropy to question the automaticity of the control. The sample entropy reflects the COP irregularity. An increase irregularity is considered to correspond to a more automatic control of movement (Donker, Roerdink, Greven, & Beek, 2007). This metric could be useful to compare our two biofeedbacks but also to investigate the external focus likely associated with Light Grip.

## 5 Conclusion

We have tested two vibrotactile biofeedbacks provided by a handle either grounded to provide Grounded Grip or not. One biofeedback constrained the drift of the participants while the other did not. The reduction of part of the COP low frequencies (drift) with the biofeedbacks only with Grounded Grip and not with Air Grip suggests that the biofeedbacks were used to re-weight the sensory information provided by the Grounded Grip. The decrease of the COP drift with both biofeedbacks and the increase of the high frequencies of the COP only with the biofeedback constraining the drift suggests that a biofeedback constraining the position of the COP in a specific "position" is less efficient as it promotes a "non-ecological" control of posture. We think that this study could be useful for the design of canes with actuated handles providing biofeedbacks. Such canes would provide both Ground Grip cues and Vibrotactile Biofeedback in one device instead of several. Indeed, this study highlights the importance of Grounded Grip cues for biofeedback use and suggests that a position biofeedback "bringing" back the individual to one position set-point might hinder postural control.



## Chapitre 6

# Conclusion

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We questioned in this thesis the possibility to voluntary control sway using Light Grip cues and vibrotactile Biofeedbacks. We chose a task of minimization of sway. The study was separated into 3 main experiments : the study of the influence of Light Grip in relaxed quiet stance (Chapter 3), the voluntary minimization of sway using Light Grip and compared to Vision (Chapter 4) and finally, the minimization of sway using two vibrotactile Biofeedbacks provided by a handle rigidly fixed to the ground or not (Chapter 5).

In the third chapter, we studied the influence of Light Grip in relaxed quiet stance using both time and frequency domain analysis. We showed that COP oscillations are reduced in the time-domain (area of the COP trajectories and COP velocity). We also showed that COP Power was reduced over the entire frequency range with a greater reduction for frequencies below  $0.5Hz$  including the drift ( $< 0.1Hz$ ). Finally, we showed that the COP of the hand on the handle and the COP of the body on the ground were correlated with the COP of the hand leading. This study highlights the usefulness of frequency analysis to study Light Grip as Light Grip does not influence all frequency bands similarly. **Light Grip has a greater influence on low frequencies.**

In the fourth chapter, we studied the voluntary control of sway using a minimization of sway task. Different sensory contexts were used : Light Grip or No Grip, Eyes Open or Eyes Closed. We found that the velocity of the COM was reduced with the instruction to minimize sway compared to standing relaxed regardless of the sensory context. We used a frequency analysis of the COP oscillations on different frequency bands. We showed that low frequency sway (COP Power  $< 0.5Hz$ ) is reduced with the minimization instruction and that Light Grip cues could be used to voluntary reduce this part of sway. We showed

that this effect was not accompanied by an increase of high frequency sway (COP Power  $> 0.5Hz$ ). We showed that there was an increased use of hip use with Light Grip compared to No Grip. We showed that for all conditions except Eyes Open No Grip, the amount of reduction of the velocity with the instruction to stand still depended on the amount of relaxed sway ; the greater the sway in relaxed stance, the greater the reduction. This study questions the theory that a minimization of sway is the goal of postural control. In brief, this chapter shows that **Light Grip cues can be used to voluntarily reduce sway**.

In the fifth chapter, we studied the voluntary control of sway using a minimization of sway task with vibrotactile biofeedbacks. The use of Vibrotactile biofeedbacks was tested with the handle grounded or not. Two different vibrotactile biofeedbacks were used. One, called Drift Constrained (DC), constrained the drift of the participant. The other, called Drift Free (DF), did not constrain the drift of the participant. In other words, participants had to minimize for both biofeedbacks but around a unique reference in space or not. Sway velocity (RMS COM Velocity) was reduced with Grounded Grip compared to Air Grip. Sway Velocity was not modified by the presence of the Biofeedback except for the Biofeedback DC with Air Grip. In this condition, the COM Velocity was increased compared to No Biofeedback. The low frequency and Drift and high frequency content of sway (using COP Power) was reduced with Grounded Grip compared to Air Grip. The drift was reduced with both Biofeedbacks but only if the Grip was Grounded. However, the Low frequencies were not modified by the presence of the Biofeedbacks. For Air Grip, the high frequencies were increased with both biofeedbacks compared to No Biofeedback. For Grounded Grip, the high frequencies were only increased for the Biofeedback constraining the Drift (DC) and not modified for the Biofeedback not constraining the drift (DF). We showed that there was an increased use of hip when the Biofeedbacks were used with Grounded Grip compared to the different Air Grips or to Grounded Grip without Biofeedback. This study highlights that a biofeedback not constraining the drift or the very slow movement of the body might be more "ecological" than a biofeedback constraining the drift or sway at a unique reference in space. We concluded that **biofeedback cues could be used to minimize sway**. Light Grip cues are likely used to reduce sway through a re-weighting by the biofeedback (Light Grip cues are given more weight as correlated with the Biofeedback cues).

In our study, we used a biofeedback that provided information regarding the direction of sway (Drift Constraining Biofeedback), we chose to use two vibrotactile actuators vibrating independently to inform the participant of the relative position of his COP outside of the Dead-Zone. The use of different encodings of the direction of sway was not investigated in this study but could affect performances. Perhaps, there are ways to provide information in terms of direction or amplitude that are more "intuitive" and

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would require less "decoding" from the participant. Following this question, we investigated tactile illusions that could convey information of direction and/or amplitude. We especially studied the Phantom Sensation. Using two vibrotactile actuators, the perception of a motion with a chosen direction can be evoked. We questioned whether a modification of the duration of the illusion could perhaps allow us to modulate the perceived amplitude of the motion or speed. Surprisingly, during preliminary investigations, we perceived that the motion could be felt out of the hand and even out of the object depending on the duration. The relationship between the duration and the distance travelled was however not evident. We thought that motions with different directions and amplitudes could be useful to provide cues of direction and amplitude in biofeedback devices but also for other tactile interfaces. Furthermore, this out-of-object perception could be very interesting to provide users with information that are not constrained in amplitude by the size of the object. We thus designed experiments to study whether this perception of out-of-hand and out-of-object was repeatable over a greater number of participants and whether the relationship between the duration and the distance travelled could be quantified. The studies are detailed in appendix D. A first study showed that that out-of-hand and out-of-object perception could be evoked and that it depended on the duration of the stimulation. However, the relationship was unclear due to at least two reasons. First, the intra-participant variability was elevated. Secondly, the position of the perceived end-point of the illusory motion could not be accurately measured due to the experiment setup. A second study was undertaken to measure with more accuracy the position of the perceived end-point. Results showed that a relationship exists between the duration and the position of the end-point. However, contrary to our first study, the perception was almost always out-of-hand for most participant. This difference of results between the two studies questions the usability of the illusion and shows that more investigation is required. Apart from the dire need of further investigating, it seemed that the illusion was not adapted to be used in our biofeedback system for several reasons. Discussion with participants after the experiments showed that the identification of the direction and position required a lot of focus. Apart from potentially withdrawing attentional resources from other processes, this would imply delay in the use of the information. Secondly, investigations not reported suggested that the perception of direction for non-naïve users was not robust; an individual can switch the direction cognitively. Furthermore, this kind of stimulation while useful to provide guidance cues for example is ill-suited for our purpose. The activation of the vibrators require that the amplitude is predefined before being sent and cannot be modulated easily according to the sway during an experiment. Given the characteristics of human sway, this seemed problematic. Finally, the amplitude cue is not perceived equally across participants complicating the use or tuning of the illusion. All these points would require investigation and are at



most hypotheses investigated with four or five individuals. Other tactile illusions might be better suited for a use in balance biofeedbacks.

In this thesis, we investigated the minimization of sway using Light Grip and Vibrotactile biofeedback cues. We showed that sway could be reduced with both Light Grip cues and Vibrotactile biofeedback cues when in presence of a grounded reference (Light Grip cues). We did not chose this task to show that posture could be stabilized with Light Grip and biofeedback cues but to show that these cues can be used to control sway. We think our findings can benefit to the design of assistive devices. For example, a cane with an actuated handle could provide a passive biofeedback (Light Grip) and an active biofeedback (Vibrotactile Biofeedback) at the same time. We think that there is much to investigate including the cognitive cost associated to the use of the Light Grip and Biofeedback cues, what kind of biofeedback encoding is the best fit and whether posture is stabilized during their use.

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# Appendices



## Annexe A

# Additional Material of the study presented in Chapter 3

### 1 Illustration of the Positions of the FSR on the handle

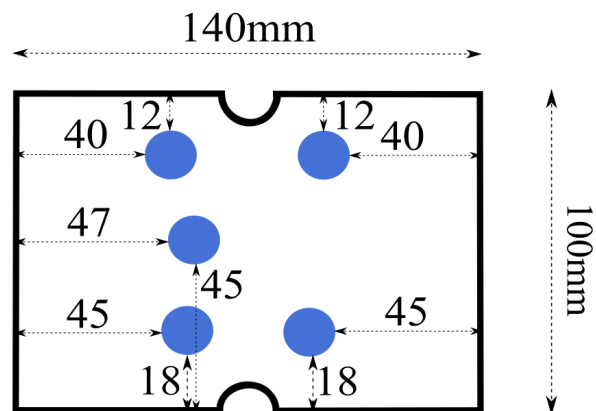


FIGURE 1: Map of the positions (in *mm*) of the FSR shown in blue on the handle surface.



## 2 Details of the 2way rm ANOVA on COP Power

### 2.1 AP direction

A two-way rm ANOVA was performed to evaluate the effect of Grip over frequency bands on COP Power in the AP direction.

There was a statistically **significant interaction between Grip and Frequency bands** on COP Power,  $F(1.33, 14.67) = 54.119, p < 0.0001, \eta^2 = 0.138$  with Greenhouse-Geisser corrections. Therefore, the effect of Grip variable was analysed for each frequency band. The **main effect of Grip** was significant for the Drift ( $F(1, 11) = 151, p < 0.0001, \eta^2 = 0.648$ ), Low frequency ( $F(1, 11) = 213, p < 0.0001, \eta^2 = 0.645$ ) and High Frequency band ( $F(1, 11) = 134, p < 0.0001, \eta^2 = 0.492$ ). The effect of Grip was smaller for the high frequency band than the drift and low frequency band. This is consistent with the less steep slope of the reduction for frequencies above  $0.5Hz$  on the Figure 4B in Chapter 3.

Pairwise comparisons, using paired t-test, show that the mean COP Power score was significantly different between Light Grip and No Grip for all frequency bands ( $p < 0.0001$ ).

The effect of frequency band variable was analysed for each Grip. The **main effect of Frequency band** was significant for the No Grip ( $F(1.4, 15.4) = 593, p < 0.0001, \eta^2 = 0.879$ ) and Light Grip ( $F(1.19, 13.1) = 109, p < 0.0001, \eta^2 = 0.707$ ) with Greenhouse-Geisser corrections. The effect of Frequency band is greater for No Grip than Light Grip. This is consistent with the slope of reduction shown in Figure 4B in Chapter 3.

For Light Grip, post-hoc pairwise comparisons, using paired t-test, show that the mean COP Power score was significantly different between Low and High Frequencies and between Drift and high frequencies ( $p < 0.0001$ ) but not between Drift and Low Frequencies ( $p = 0.099$ ).

For No Grip, pairwise comparisons, using paired t-test, show that the mean COP Power score was significantly different between Low and High Frequencies, between Drift and Low frequencies and between Drift and High frequencies ( $p < 0.0001$ ).

Results of pairwise comparisons and descriptive statistics (mean and standard deviation) are summarized in Tables 1 and 2 in Chapter 3.

## 2.2 ML direction

A two-way rm ANOVA was performed to evaluate the effect of Grip over Frequency Bands on COP Power in the ML direction.

The analysis revealed a significant **main effect of Grip** on COP Power ( $F(1, 11) = 64.58, p < 0.0001, \eta^2 = 0.185$ ) and a significant **main effect of Frequency band** on COP Power ( $F(1.26, 13.85) = 91.228, p < 0.0001, \eta^2 = 0.647$ ) with Greenhouse-Geisser corrections.

Pairwise comparisons, using paired t-test, show that the mean COP Power score was significantly different between Light Grip and No Grip for all frequency bands ( $p < 0.0001$  for the Drift and Low Frequency band and  $p = 0.001$  for the High Frequency band).

For Light Grip, pairwise comparisons, using paired t-test, show that the mean COP Power score was significantly different between Low and High Frequencies and between Drift and high frequencies ( $p < 0.0001$ ) but not between Drift and Low Frequencies ( $p = 0.065$ ).

For No Grip, pairwise comparisons, using paired t-test, show that the mean COP Power score was significantly different between Low and High Frequencies, between Drift and High frequencies ( $p < 0.0001$ ) and between Drift and Low frequencies ( $p = 0.00032$ ).

### 3 Study of the Orientation Axes of the Ellipses of the COP of the Body and Hand applied to the handle

An illustration of the trajectory and ellipse of  $COP_b$  and  $COP_h$  normalized is shown in Figure 2A and the orientation of the axes of the ellipses in Figure 2B.

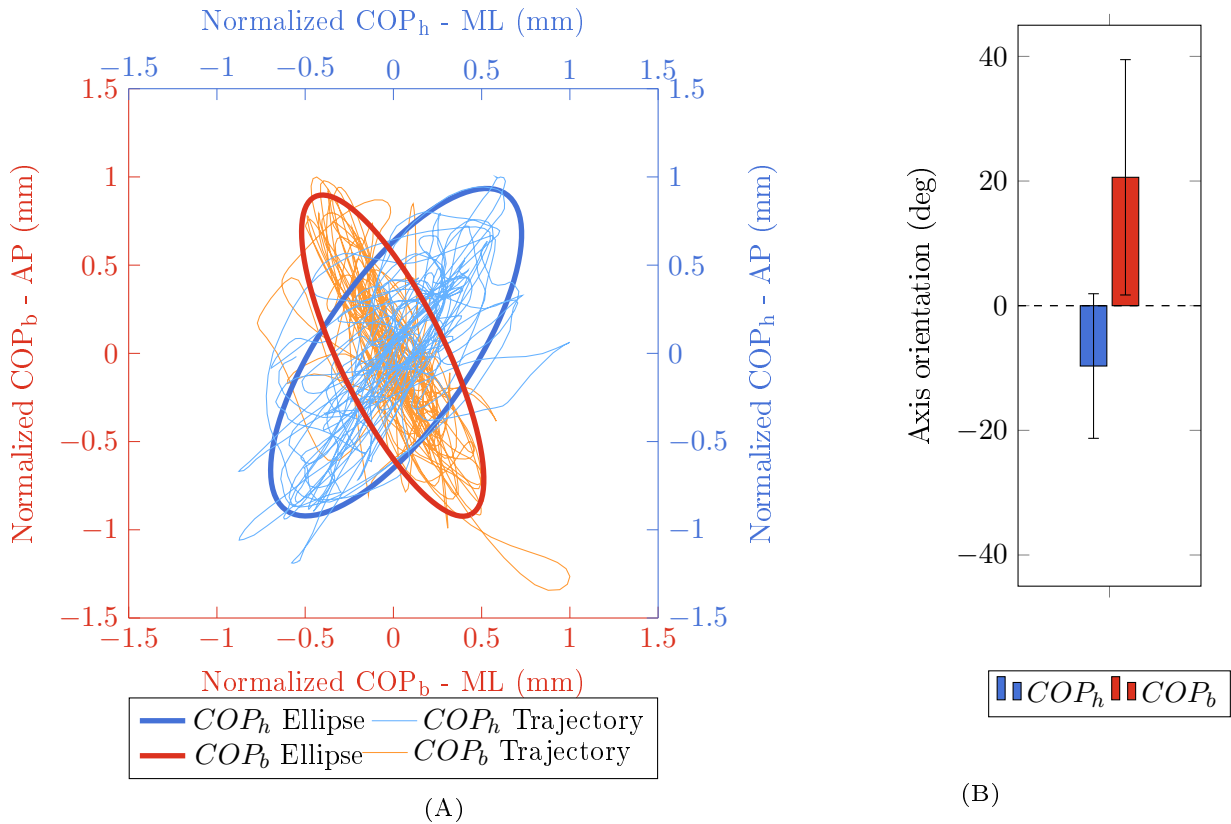


FIGURE 2: Illustration of the orientation of the ellipse of the COP of the body on the ground ( $COP_b$ ) and Center of Pressure of the hand ( $COP_h$ ) with (A) Normalized Ellipses of the trajectory of  $COP_b$  and  $COP_h$  and (B) Barplot of the orientation axes in degrees.

	$COP_b$	$COP_h$	N
Mean $\pm$ std	$20.60 \pm 18.88$	$-9.68 \pm 11.6$	12
Angle difference (P-value)	$p = 0.0029$		12

TABLE 1: Descriptive statistics (mean  $\pm$  standard deviation) and P-value of the difference between the  $COP_b$  and  $COP_h$  ellipses orientation axes for N participants.

The axis of orientation of the COP of the hand on the handle ellipse is not collinear with the axis of orientation of the COP of the body on the ground ellipse. The **difference in orientation** of  $COP_b$  and  $COP_h$  ellipses is **significant** ( $F(1, 11) = 14.38$ ,  $p = 0.0029$ , 1-way repeated measures ANOVA).

## Annexe B

# Additional Material of the Study Presented in the Chapter 4

### 1 On the Use of the Median Frequency index

Many studies use the median or mean frequency to study changes in postural sway. We can mention for example the study of [Menevin et Wulf \(2002\)](#) which compared internal and external focus during Light Touch with a curtain.

We would like to comment on the use of the median frequency in absence of PSD plots to comment on differences between conditions and to discuss change of neuromuscular activity.

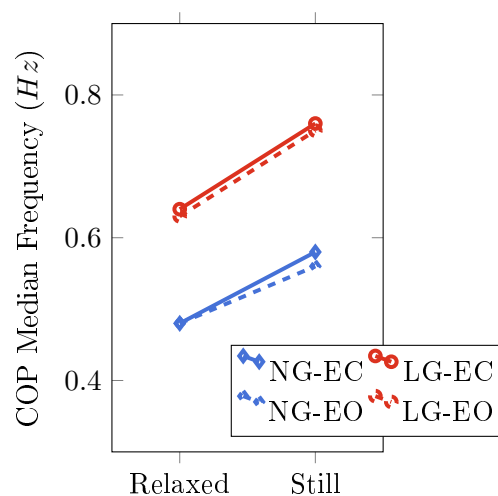


FIGURE 1: COP Median Frequency for all conditions for all participants. Blue Squares and red circles represent No Grip and Light Grip, respectively. Bold and dashed lines represent Eyes Closed and Eyes Open, respectively.

The Figure 1 shows the median frequency for all conditions. The effect of Instruction (positive slope) and Grip (red lines are above blue lines) are visible. The statistical analysis shows a main effect of Instruction ( $F(1, 12) = 37.238$ ,  $p = .00005$  and  $\eta^2 = 0.170$ ) and Grip ( $F(1, 12) = 108.59$ ,  $p < .0001$  and  $\eta^2 = 0.347$ ). This means that the median frequency is increased with the instruction and with Grip. This could be interpreted as an increase of COP high frequency content and hence possibly further interpreted as an increased stiffness. However, observations of PSD plots of all conditions and study of the power on different frequency bands shows that the increased median frequency is not simply the result of an increase of the COP high frequency content. For low frequencies, where the power is greatest, the power is significantly reduced by the Instruction and by Grip. For high frequencies, where the power is smallest, the power is not significantly reduced by the Instruction and reduced in a lesser amount than for low frequencies by Grip. This different reduction of low and high frequencies causes a shift of the median frequency. We think that the median frequency index should not be used in absence of PSD plots as their study, alone might be misleading during the interpretation of the results. The use of the mean frequency could be questioned with an analogous reasoning.



## 2 PSD Plots of Each Participant

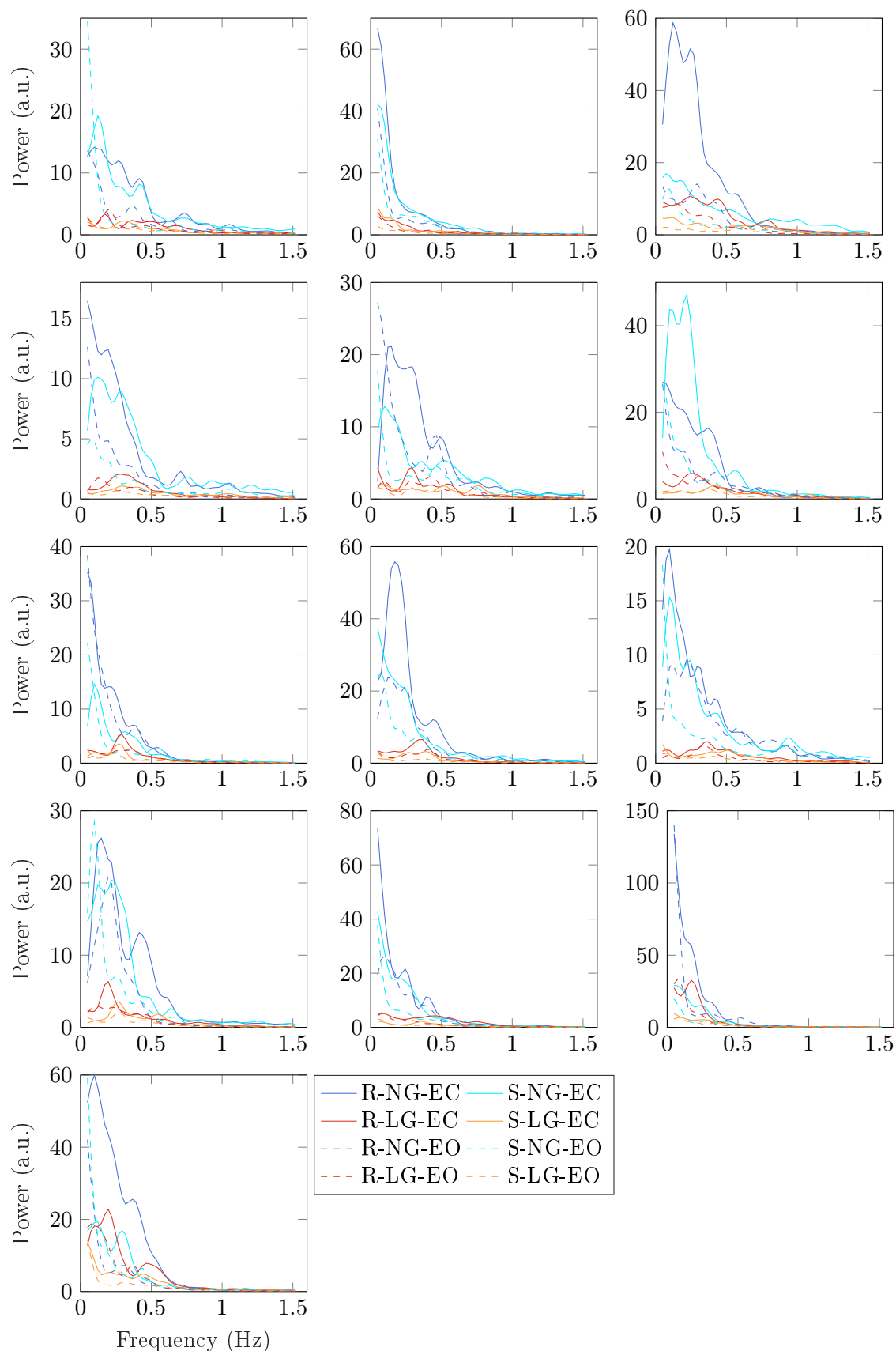


FIGURE 2: COP PSD estimates for each condition for each participant (S : Still; R : Relaxed; NG : No Grip; LG : Light Grip; EC : Eyes Closed; EO : Eyes Open). Note the variability of the 12th participant compared to the others.

### 3 Details of the 3-way rm Anova on RMS COM Velocity

A three-way repeated measures ANOVA was performed to evaluate the effects of Instruction, Vision and Grip on RMS COM Velocity.

The effect of instruction on sway velocity The Instruction to reduce sway had a significant effect on sway velocity (**main effect of instruction**,  $F(1, 12) = 13.55$ ,  $p = .003$ ,  $\eta^2 = 0.153$ ).

Pairwise comparisons, using paired t-tests, showed that Instruction had a significant effect for all conditions with  $p = .032$  for the No Grip Eyes Closed,  $p = .011$  for Light Grip Eyes Closed,  $p = .009$  for No Grip Eyes Open and  $p = .00002$  for the Light Grip Eyes Open.

*Summary* : Sway velocity is reduced with the Instruction to stand still for all sensory conditions ( $S < R$ ).

The effect of Sensory context (Grip and Vision) on sway velocity :

The analysis revealed a **two-way interaction between Vision and Grip** on sway velocity ( $F(1, 12) = 32.98$ ,  $p = .00009$ ,  $\eta^2 = .054$ ). Therefore, the effect of grip was studied for Eyes Closed and Eyes Open separately. A **main effect of Grip** was found for both Eyes Closed ( $F(1, 25) = 288.$ ,  $p < .0001$ ,  $\eta^2 = 0.498$ ) and Eyes Open ( $F(1, 25) = 106.$ ,  $p < .0001$ ,  $\eta^2 = 0.361$ ) with a greater effect of Grip for Eyes Closed. The effect of Vision was studied for No Grip and for Light Grip separately. A **main effect of Vision** was found for both No Grip ( $F(1, 25) = 78.5$ ,  $p < .0001$ ,  $\eta^2 = 0.274$ ) and Light Grip ( $F(1, 25) = 33.6$ ,  $p < .0001$ ,  $\eta^2 = .058$ ) with a greater effect of Vision for No Grip. Both Grip and Vision had a greater effect in the absence of the other sensory information.

Pairwise comparisons, using paired t-tests, showed that Grip had a significant effect for all conditions with  $p < .0001$  for Relaxed Eyes Closed, Still Eyes Closed and Still Eyes Open and for Relaxed Eyes Open.

Pairwise comparisons, using paired t-tests, showed that Vision had a significant effect for all conditions with  $p < .0001$  for Still No Grip and Still Light Grip, with  $p = .018$  for Relaxed Light Grip and  $p = .00011$  for Relaxed No Grip.



## 4 Details of the 3-way rm Anova on COP Power for the entire frequency range

A three-way repeated measures ANOVA was performed to evaluate the effects of Instruction, Vision and Grip on COP Power for the entire frequency range.

The test revealed a significant **two-way interaction between Grip and Vision** ( $F(1, 12) = 10.427, p = .007, \eta^2 = .013$ ) and a significant **two-way interaction between Grip and Instruction** ( $F(1, 12) = 5.053, p = .044, \eta^2 = .010$ ).

Following the Grip x Vision interaction, the effect of Grip was studied for Eyes Open and Eyes Closed separately revealing a **main effect of Grip for Eyes Closed** ( $F(1, 25) = 354, p < .0001, \eta^2 = 0.663$ ) and a **main effect of Grip for Eyes Open** ( $F(1, 25) = 148, p < .0001, \eta^2 = 0.573$ ) on COP Power. The effect of Grip was greater for Eyes Closed.

Following the Grip x Vision interaction, the effect of Vision was studied for No Grip and Light Grip separately revealing a **main effect of Vision for No Grip** ( $F(1, 25) = 96.3, p < .0001, \eta^2 = 0.353$ ) and a **main effect of Vision for Light Grip** ( $F(1, 25) = 84.5, p < .0001, \eta^2 = .081$ ) on COP Power. The effect of Vision was greater for No Grip.

For Grip and Vision, the effect is greater in the absence of the other sensory source (Grip has a greater influence in the absence of Vision and Vision has a greater influence in the absence of Grip).

Following the Grip x Instruction interaction, the effect of Instruction was studied for No Grip and Light Grip separately revealing a **main effect of Instruction for No Grip** ( $F(1, 25) = 20.0, p = .0003, \eta^2 = 0.12$ ) and a **main effect of Instruction for Light Grip** ( $F(1, 25) = 94.6, p < .0001, \eta^2 = 0.17$ ) on COP Power. The effect of Instruction was greater for Light Grip.

Following the Grip x Instruction interaction, the effect of Grip was studied for Relaxed and Still separately revealing a **main effect of Grip for Relaxed** ( $F(1, 25) = 184, p < .0001, \eta^2 = 0.531$ ) and a **main effect of Grip for Still** ( $F(1, 25) = 258, p < .0001, \eta^2 = 0.693$ ) on COP Power. The effect of Grip was greater for Still conditions.

Following significant main effects of Grip, Vision and Instruction, pairwise comparisons were performed.

Pairwise comparisons, using t-test, showed that Light Grip was different from No Grip for Relaxed Eyes Closed, Still Eyes Closed, Still Eyes Open ( $p < .0001$ ) and Relaxed Eyes Open ( $p < .0001$ ).

## 5. Details of the 3-way rm Anova on COP Power for the low frequency band

Pairwise comparisons, using t-test, showed that Eyes Open was different from Eyes Closed for Relaxed No Grip, Still No Grip, Still Light Grip ( $p < .0001$ ) and Relaxed Light Grip ( $p < .0001$ ).

Pairwise comparisons, using t-test, showed that Still was different from Relaxed for Eyes Closed No Grip ( $p = .008$ ), for Eyes Open No Grip ( $p = .011$ ), Eyes Open Light Grip ( $p < .0001$ ) and Eyes Closed Light Grip ( $p < .0001$ ).

## 5 Details of the 3-way rm Anova on COP Power for the low frequency band

A three-way repeated measures ANOVA was performed to evaluate the effects of Instruction, Vision and Grip on the power on the low frequency band ( $[0.04 - 0.5Hz]$ ).

The test revealed a significant **two-way interaction between Grip and Vision** ( $F(1, 12) = 11.915$ ,  $p = .005$ ,  $\eta^2 = .015$ ) and a significant **two-way interaction between Grip and Instruction** ( $F(1, 12) = 7.487$ ,  $p = .018$ ,  $\eta^2 = .015$ ).

Following the Grip x Vision interaction, the effect of Grip was studied for Eyes Open and Eyes Closed separately revealing a **main effect of Grip for Eyes Closed** ( $F(1, 25) = 363$ ,  $p < .0001$ ,  $\eta^2 = 0.659$ ) and a **main effect of Grip for Eyes Open** ( $F(1, 25) = 159$ ,  $p < .0001$ ,  $\eta^2 = 0.556$ ) on COP Power. The effect of Grip was greater for Eyes Closed.

Following the Grip x Vision interaction, the effect of Vision was studied for No Grip and Light Grip separately revealing a **main effect of Vision for No Grip** ( $F(1, 25) = 99.2$ ,  $p < .0001$ ,  $\eta^2 = 0.308$ ) and a **main effect of Vision for Light Grip** ( $F(1, 25) = 60.7$ ,  $p < .0001$ ,  $\eta^2 = .057$ ) on COP Power. The effect of Vision was greater for No Grip.

For Grip and Vision, the effect is greater in the absence of the other sensory source (Grip has a greater influence in the absence of Vision and Vision has a greater influence in the absence of Grip).

Following the Grip x Instruction interaction, the effect of Instruction was studied for No Grip and Light Grip separately revealing a **main effect of Instruction for No Grip** ( $F(1, 25) = 25.2$ ,  $p < .0001$ ,  $\eta^2 = 0.148$ ) and a **main effect of Instruction for Light Grip** ( $F(1, 25) = 130$ ,  $p < .0001$ ,  $\eta^2 = 0.219$ ) on COP Power. The effect of Instruction was greater for Light Grip.

Following the Grip x Instruction interaction, the effect of Grip was studied for Relaxed and Still separately revealing a **main effect of Grip for Relaxed** ( $F(1, 25) = 190$ ,

$p < .0001$ ,  $\eta^2 = 0.539$ ) and a **main effect of Grip for Still** ( $F(1, 25) = 288$ ,  $p < .0001$ ,  $\eta^2 = 0.704$ ) on COP Power. The effect of Grip was greater for Still conditions.

Following significant main effects of Grip, Vision and Instruction, pairwise comparisons were performed.

Pairwise comparisons, using t-test, showed that Light Grip was different from No Grip for Relaxed Eyes Closed, Still Eyes Closed, Still Eyes Open ( $p < .0001$ ) and Relaxed Eyes Open ( $p < .0001$ ).

Pairwise comparisons, using t-test, showed that Eyes Open was different from Eyes Closed for Relaxed No Grip, Still No Grip, Still Light Grip ( $p < .0001$ ) and Relaxed Light Grip ( $p < .0001$ ).

Pairwise comparisons, using t-test, showed that Still was different from Relaxed for Eyes Closed No Grip ( $p = .004$ ), for Eyes Open No Grip ( $p = .005$ ), Eyes Open Light Grip and Eyes Closed Light Grip ( $p < .0001$ ).

## 6 Details of the 3-way rm Anova on COP Power for the drift band

A three-way repeated measures ANOVA was performed to evaluate the effects of Instruction, Vision and Grip on the COP Power on the frequency band corresponding to the drift ( $[0.04 - 0.1Hz]$ ).

There was a **main effect of Instruction** ( $F(1, 12) = 18.9$ ,  $p = .0009$ ,  $\eta^2 = .008$ ).

Pairwise comparisons, using t-tests, show that Relaxed and Still stance were significantly different for all conditions except Eyes Open No Grip ( $p = .001$  for Eyes Closed Light Grip,  $p = .0007$  for Eyes Open Light Grip,  $p = .016$  for Eyes Closed No Grip and  $p = .368$  for Eyes Open No Grip).

The **two-way interaction between Vision and Grip** on COP Power was significant ( $F(1, 12) = 7.5$ ,  $p = .018$ ,  $\eta^2 = .012$ ). Therefore, the effect of Grip was studied for Eyes Closed and Eyes Open separately. **Grip had a significant main effect on Eyes Closed** on COP Power ( $F(1, 25) = 265$ ,  $p < .0001$ ,  $\eta^2 = 0.662$ ) **and Eyes Open** conditions ( $F(1, 25) = 146$ ,  $p < .0001$ ,  $\eta^2 = 0.579$ ). **Vision had a significant main effect on COP Power for No Grip** conditions only ( $F(1, 25) = 16.7$ ,  $p = .0008$ ,  $\eta^2 = 0.1$ ),  $F(1, 25) = 0.18$ ,  $p = 1$ ,  $\eta^2 = .0004$  for Light Grip.

Pairwise comparisons show that Light Grip and No Grip conditions are significantly different for all conditions ( $p \leq .00001$ ) and that Eyes Closed and Eyes Open conditions

were different for the No Grip Relaxed condition ( $p = .004$ ) but not for No Grip Still condition ( $p = .05$ ).

## 7 Details of the 3-way rm Anova on COP Power for the High Frequency Band

A three-way repeated measures ANOVA was performed to evaluate the effects of Instruction, Vision and Grip on the power on the high frequency band ( $[0.5 - 1.5Hz]$ ).

**Main effect of Vision** ( $F(1, 12) = 35.2, p = .00007, \eta^2 = 0.198$ ) and **main effect of Grip** ( $F(1, 12) = 57.3, p = .000006, \eta^2 = 0.413$ ) on COP Power are statistically significant. The effect of Grip is greater than the effect of Vision.

Pairwise comparisons show that Light Grip is significantly different from No Grip for all conditions ( $p < .0005$ ), that Eyes Closed and Eyes Open are significantly different all conditions ( $p = .015$  for Relaxed Light Grip,  $p = .011$  for Relaxed No Grip conditions and  $p \leq .0005$  for still conditions).

## 8 Boxplot of the COP Power before log-transformation

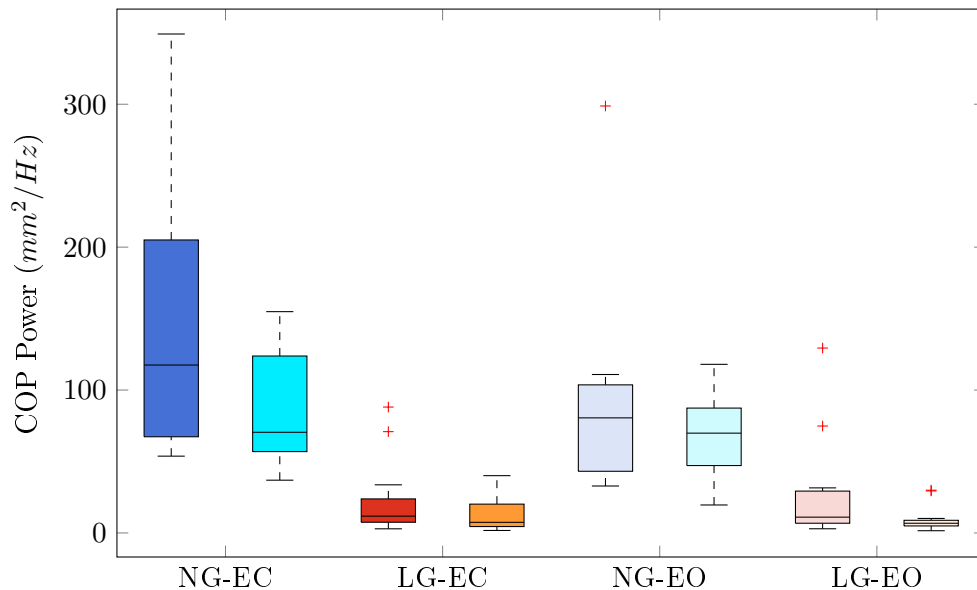


FIGURE 3: COP total Power for the drift band for each condition (NG : No Grip ; LG : Light Grip ; EC : Eyes Closed ; EO : Eyes Open) for all participants pooled together except participant excluded. Relaxed are in dark blue or red and Still are in light blue or orange. Light Grip conditions shown in light and dark red are clearly below No Grip conditions shown in light and dark blue. Still conditions shown in light blue or red are mostly below Relaxed conditions shown in dark blue or red.

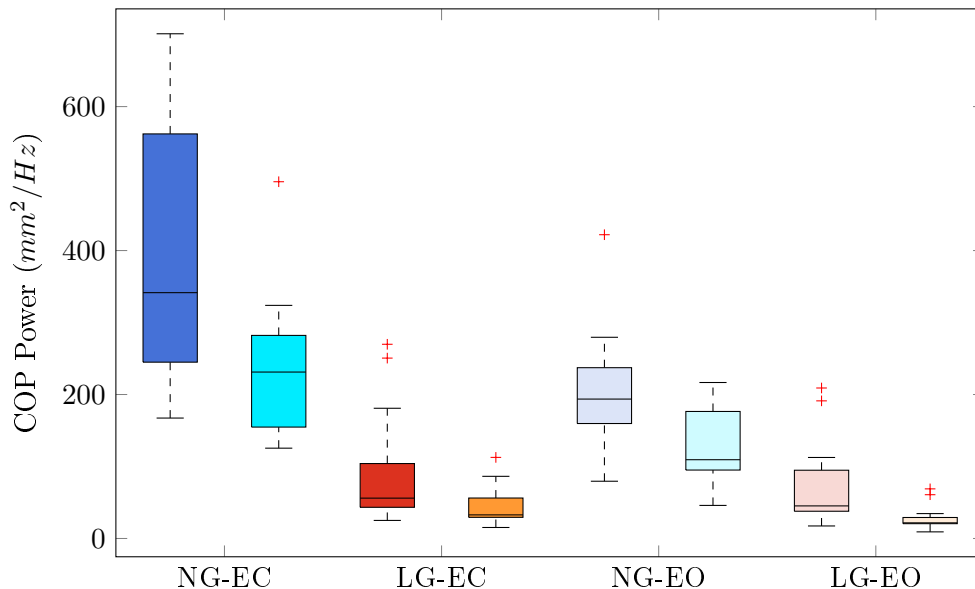


FIGURE 4: COP total Power for the low frequency band for each condition (NG : No Grip; LG : Light Grip; EC : Eyes Closed; EO : Eyes Open) for all participants pooled together except participant excluded. Relaxed are in dark blue or red and Still are in light blue or orange. Light Grip conditions shown in light and dark red are clearly below No Grip condition shown in light and dark blue. Still conditions shown in light blue or red are mostly below Relaxed conditions shown in dark blue or red.

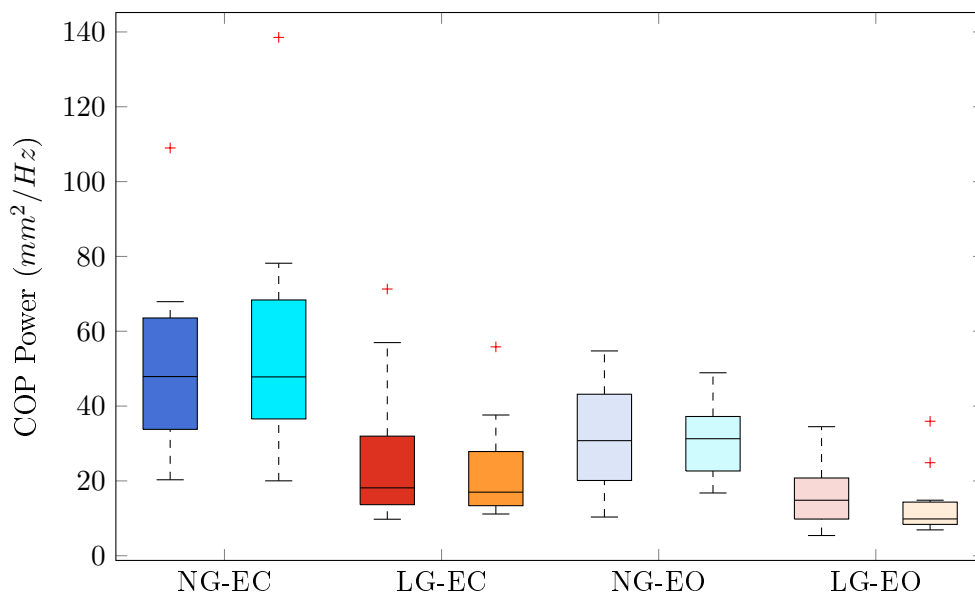


FIGURE 5: COP total Power for the high frequency band for each condition (NG : No Grip; LG : Light Grip; EC : Eyes Closed; EO : Eyes Open) for all participants pooled together except participant excluded. Relaxed are in dark blue or red and Still are in light blue or orange. Light Grip conditions shown in light and dark red seem below No Grip condition shown in light and dark blue. Still conditions shown in light blue or red are mostly below Relaxed conditions shown in dark blue or red.

# Annexe C

## Additional Material of the Study Presented in the Chapter 5

### 1 Preliminary Experiment

#### 1.1 Objective of the Preliminary Experiment

The preliminary experiment was used to test the intelligibility of the biofeedback DC. The part of the handle vibrating is providing information to the participant regarding the position of his/her Center of Pressure relative to the Dead-zone. This experiment was thus designed to test whether the participants were able to discriminate which part of the handle was vibrating (anterior vs posterior part) for different frequencies of vibration.

To that end, vibrations of the anterior or posterior part of the handle of two different frequencies were presented to the participant. This was done for the handle rigidly fastened or free.

#### 1.2 Methods

##### 1.2.1 Experimental Setup

The handle used was the same as the one used in the main experiment. A USB NI acquisition card was used to generate the stimuli at  $4kHz$ . Audio Amplifiers were used to amplify the output of the acquisition card. The gain of amplification was the same as for the main experiment. Matlab software was used to generate the stimuli and record the answer of the participants.

The experimental setup is presented in Figure 1.

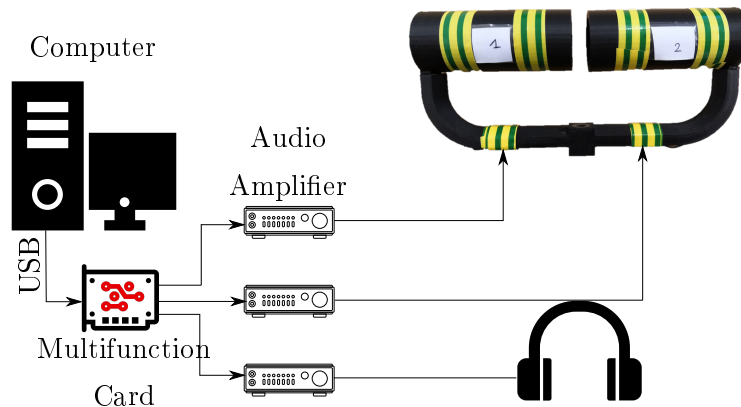


FIGURE 1: Experimental Setup of the Preliminary Experiment

### 1.2.2 Stimuli used

During the balance trials, the biofeedback is "continuous" and of varying frequency outside the dead-zone. To facilitate the undergoing of the preliminary experiment and to avoid fatigue, isolated vibrations of constant frequency are presented to the participant. The frequencies presented during the preliminary experiments have been chosen as likely experienced by the participant in the balance trials.

The produced stimuli are sine waves of constant intensity and of 1s duration. The intensity was the same as in the main experiment. The frequencies  $F1$  and  $F2$  used for the preliminary experiment were of  $100Hz$  and  $200Hz$ . These frequency correspond to a COP of  $2mm$  and  $4mm$  of amplitude respectively as a gain of 50 is used for the modulation of the frequency.

### 1.2.3 Experimental Conditions

The two parts of the handle were vibrated independently. The anterior and posterior part of the handle were vibrated using the two stimuli. The two fastening conditions were tested, in other words, the trials were performed with the handle rigidly fastened to the ground and free (untethered).

### 1.2.4 Experimental Procedure

Participants were comfortably seated. We chose to test the intelligibility of the feedback while the participants were seated as we only want to test the intelligibility without any possible interference of postural sway. Participants wore headphones playing pink

noise and closed their eyes during the stimulations in order to avoid any auditory and visual biases. Participants held the handle in their dominant hand. The experimenter ensured that the participants' grasp was evenly distributed on the two parts of the handle.

Participants were explained that they would be presented a vibration, either in the anterior or posterior part of the handle. Participants were asked to identify whether it was the anterior or the posterior part vibrating, regardless of the frequency, after the stimulation. For each part of the handle, 5 trials of the 2 frequencies were presented to the participant. This was done for the handle rigidly fastened to the ground and for the one untethered. This amounted to a total of 40 trials. The trials were presented divided into 2 parts of 20 trials based on the fastening of the handle. The first part was either with the handle fastened or free, this was randomly chosen. Inside the parts, the frequencies and part vibrating (anterior vs posterior part) were randomized. A 2-minute break was added between the first and second part. A break was taken whenever the participant asked for one. The preliminary experiment took no more than 10 minutes, explanations included.

### 1.2.5 Data Collection and Analysis of the Preliminary Experiment

**Data Collection** Participants reported orally which part was vibrating to the experimenter. Matlab Software was used to record the participants' answers.

**Analysis** For each participant, the number of correct identifications of the vibrating part was computed independently for each part and for each Grip. The mean and standard deviation were then computed.

## 1.3 Results and Conclusion

The results of the preliminary experiment presented in Table 1 reveal that participants identified almost perfectly the part that was vibrating. An incorrect identification of the part vibrating is thus not a likely explanation for surprising effects of the Biofeedback.

		Grip	
		Air Grip	Grounded Grip
Part	Anterior	96 ± 8	96 ± 12
	Posterior	98 ± 3	100

TABLE 1: Percentage of correct identification (*mean ± std*) of the vibrating part for the handle attached (Grounded Grip) or untethered (Air Grip)





## 2 PSD Plots of Each Participant

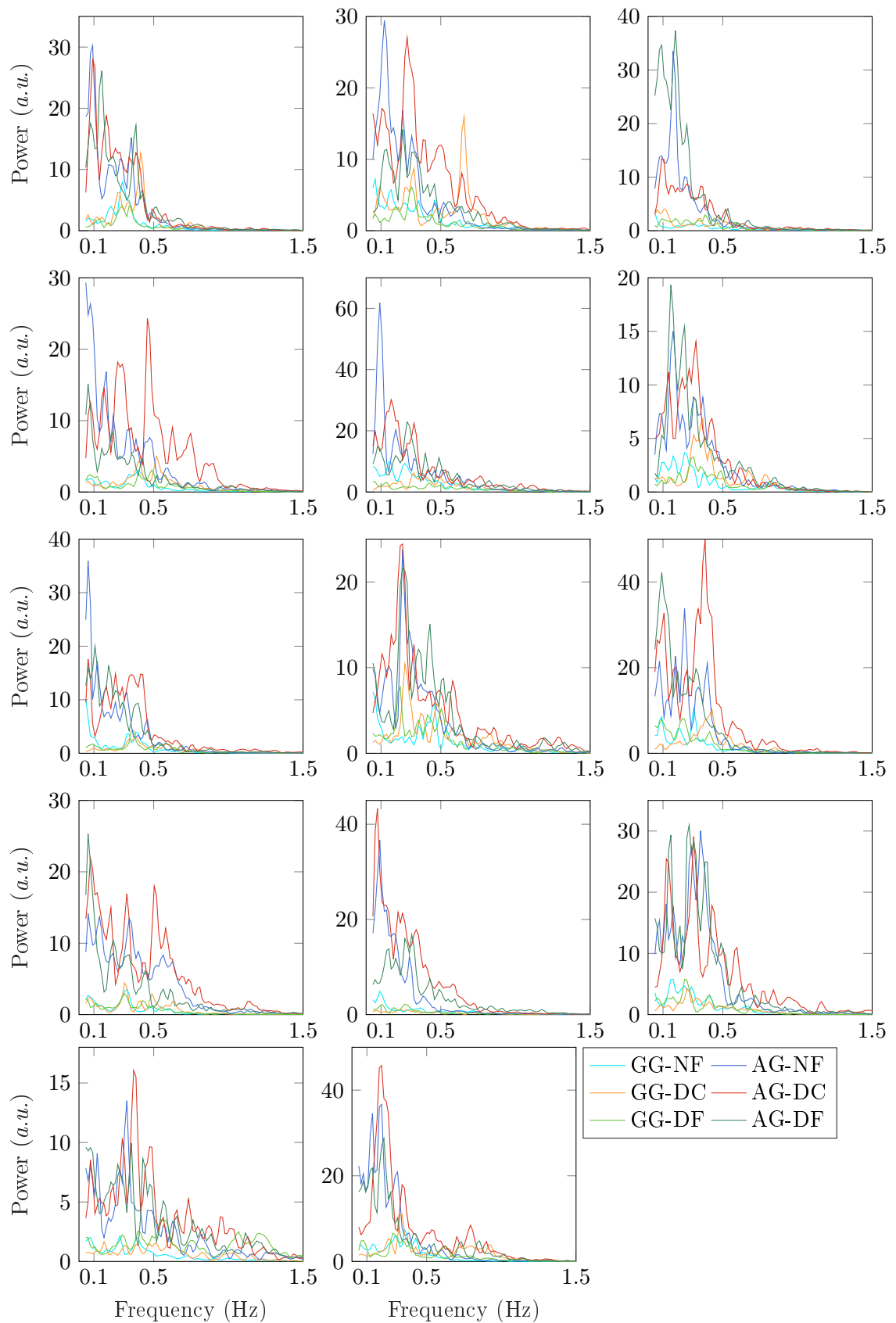


FIGURE 2: COP PSD estimates for each condition for each participant (NF : No Biofeedback; DC : Biofeedback DC; DF : Biofeedback DF; AG : Air Grip; GG : Grounded Grip).

### 3 Details of the 2-way rm Anova on RMS COM Velocity

A two-way repeated measures ANOVA was performed to evaluate the effects of Biofeedback and Grip on RMS COM Velocity.

Main effects and interactions : A **significant main effect of Grip** was found ( $F(1, 13) = 167.222, p < .0001, \eta^2 = .625$ ). A **significant main effect of Biofeedback** was found ( $F(1.61, 20.90) = 9.001, p = .003, \eta^2 = .102$ ). However, no significant interaction between Grip and Biofeedback was found ( $F(1.41, 18.39) = 2.64, p = .112, \eta^2 = .019$ ).

Pairwise comparisons between Air Grip and Grounded Grip for all Biofeedbacks : Pairwise comparisons show that Grounded Grip is significantly different from Air Grip for all conditions ( $p < .0001$ ).

Pairwise comparisons between No Biofeedback, Biofeedback DC and Biofeedback DF for Grounded Grip : Pairwise comparisons show that No Biofeedback is not different from Biofeedback DF with Grounded Grip ( $p > .99$ ) and that No feedback is not different from Biofeedback DC with Grounded Grip ( $p = .057$ ). Biofeedback DC is not different from Biofeedback DF with Grounded Grip ( $p = .098$ ).

Pairwise comparisons between No Biofeedback, Biofeedback DC and Biofeedback DF for Air Grip : Pairwise comparisons show that No Biofeedback is not different from Biofeedback DF with Air Grip ( $p = .75$ ), that Biofeedback DC is not different from Biofeedback DF with Air Grip ( $p = .15$ ). However, No feedback is different from Biofeedback DC with Air Grip ( $p = .0009$ ).

### 4 Details of the 2-way rm Anova on COP Power for the Entire Frequency Range

A two-way repeated measures ANOVA was performed to evaluate the effects of Biofeedback and Grip on COP Power for the entire frequency range.

Main effects and interactions : A **significant main effect of Grip** was found ( $F(1, 13) = 238.823, p < .0001, \eta^2 = 0.782$ ). A **significant main effect of Biofeedback** was found ( $F(1.64, 21.33) = 4.865, p = .023, \eta^2 = .058$ ). However, no significant interaction between Grip and Biofeedback was found ( $F(1.85, 24.01) = 0.238, p = .773, \eta^2 = .002$ ).

Pairwise comparisons between Air Grip and Grounded Grip for all Biofeedbacks : Pairwise comparisons show that Grounded Grip is significantly different from Air Grip for all conditions ( $p < .0001$ ).

Pairwise comparisons between No Biofeedback, Biofeedback DC and Biofeedback DF for Grounded Grip : Pairwise comparisons show that No Biofeedback is not different from Biofeedback DF with Grounded Grip ( $p > .99$ ) and that No feedback is not different from Biofeedback DC with Grounded Grip ( $p = .522$ ). Biofeedback DC is not different from Biofeedback DF with Grounded Grip ( $p = .363$ ).

Pairwise comparisons between No Biofeedback, Biofeedback DC and Biofeedback DF for Air Grip : Pairwise comparisons show that No Biofeedback is not different from Biofeedback DF with Air Grip ( $p > .99$ ), that Biofeedback DC is not different from Biofeedback DF with Air Grip ( $p = .148$ ). However, No feedback is different from Biofeedback DC with Air Grip ( $p = .002$ ).

## **5 Details of the 2-way rm Anova on COP Power for the Low Frequency Band**

A two-way repeated measures ANOVA was performed to evaluate the effects of Biofeedback and Grip on COP Power on the low frequency band  $0.04 - 0.5Hz$ . The statistical analysis shows only an effect of Grip.

Main effects and interactions : A **significant main effect of Grip** was found ( $F(1, 13) = 288.718, p < .0001, \eta^2 = 0.798$ ). However, no main effect of Biofeedback was found for this frequency band ( $F(1.69, 21.98) = 2.08, p = .155, \eta^2 = .022$ ) and no significant interaction between Grip and Biofeedback was found ( $F(1.69, 22.03) = 1.486, p = .247, \eta^2 = .012$ ) as well.

Pairwise comparisons between Air Grip and Grounded Grip for all Biofeedbacks : Pairwise comparisons show that Grounded Grip is significantly different from Air Grip for all conditions ( $p < .0001$ ).

## **6 Details of the 2-way rm Anova on COP Power for the Drift Band**

A two-way repeated measures ANOVA was performed to evaluate the effects of Biofeedback and Grip on the COP power on the frequency band corresponding to the drift ( $[0.04 - 0.1Hz]$ ). The statistical analysis shows a effect of Biofeedback and of Grip.

Main effects and interactions : A **significant main effect of Biofeedback** was found for this frequency band ( $F(1.94, 25.16) = 6, p = 0.008, \eta^2 = 0.123$ ). A **significant main effect of Grip** was found ( $F(1, 13) = 269.2, p < .0001, \eta^2 = 0.744$ ). In contrast, no significant interaction between Grip and Biofeedback was found ( $F(1.62, 21.08) = 2.781, p = .094, \eta^2 = 0.037$ ).

Pairwise comparisons between Air Grip and Grounded Grip for all Biofeedbacks : Pairwise comparisons show that Grounded Grip is significantly different from Air Grip for all conditions ( $p < .0001$ ).

Pairwise comparisons between No Biofeedback, Biofeedback DC and Biofeedback DF for Grounded Grip : Pairwise comparisons show that No Biofeedback is different from Biofeedback DF with Grounded Grip ( $p = .018$ ) and that No Biofeedback is different from Biofeedback DC with Grounded Grip ( $p = .01$ ). Biofeedback DC is not different from Biofeedback DF with Grounded Grip ( $p = 0.558$ ).

Pairwise comparisons between No Biofeedback, Biofeedback DC and Biofeedback DF for Air Grip : Pairwise comparisons show that No Biofeedback is not different from Biofeedback DF with Air Grip ( $p = .66$ ) and that No Biofeedback is not different from Biofeedback DC with Air Grip ( $p = .441$ ) and that Biofeedback DC is not different from Biofeedback DF with Air Grip ( $p > .99$ ).

## 7 Details of the 2-way rm Anova on COP Power for the High Frequency Band

A two-way repeated measures ANOVA was performed to evaluate the effects of Biofeedback and Grip on the COP Power for the high frequency band ( $[0.5 - 1.5Hz]$ ). The analysis showed an effect of Biofeedback and Light Grip.

Main Effects and Interactions : A **significant main effect of Biofeedback** was found for this frequency band ( $F(1.77, 23.02) = 27.9, p < .0001, \eta^2 = .259$ ). A **significant main effect of Grip** was found ( $F(1, 13) = 73.06, p < 0.0001, \eta^2 = .447$ ). However, no significant interaction between Grip and Biofeedback was found ( $F(1.84, 23.95) = .166, p = 0.831, \eta^2 = .002$ ).

Pairwise comparisons between Air Grip and Grounded Grip for all Biofeedbacks : Pairwise comparisons show that Grounded Grip is significantly different from Air Grip for all conditions ( $p < .001$ ).

Pairwise comparisons between No Biofeedback, Biofeedback DC and Biofeedback DF for Grounded Grip : Pairwise comparisons show that No Biofeedback is different from

Biofeedback DC with Grounded Grip ( $p = .0007$ ), that No Biofeedback is not different from Biofeedback DF with Grounded Grip ( $p = .2$ ) and that Biofeedback DF is not different from Biofeedback DC with Grounded Grip ( $p = .069$ ).

Pairwise comparisons between No Biofeedback, Biofeedback DC and Biofeedback DF for Air Grip : Pairwise comparisons show that No Biofeedback is different from Biofeedback DC for Air Grip ( $p < .0001$ ), that No Biofeedback is different from Biofeedback DF for Air Grip ( $p = .015$ ) and that Biofeedback DF is different from Biofeedback DC for Air Grip ( $p = .019$ ).

## 8 Details of the 2-way rm Anova on Hip and Shoulder Correlation

A two-way repeated measures ANOVA was performed to evaluate the effects of Biofeedback and Grip on the shoulder and hip correlation. the statistical analysis shows an effect of Biofeedback and Grip on shoulder and hip correlation.

Main Effects and Interactions : A **significant main effect of Biofeedback** was found ( $F(1.95, 23.39) = 13.217, p = .00016, \eta^2 = .153$ ). A **significant main effect of Grip** was found ( $F(1, 12) = 16.755, p = .001, \eta^2 = .158$ ). However, no significant interaction between Grip and Biofeedback was found ( $F(1.98, 23.74) = 2.856, p = .078, \eta^2 = .046$ ).

Pairwise comparisons between Air Grip and Grounded Grip for all Biofeedbacks : Pairwise comparisons show that Grounded Grip is significantly different from Air Grip for Biofeedback DC ( $p = .004$ ) and DF ( $p = .002$ ) but not without Biofeedback ( $p = .466$ ).

Pairwise comparisons between No Biofeedback, Biofeedback DC and Biofeedback DF for Grounded Grip : Pairwise comparisons show that No feedback is different from Biofeedback DC with Grounded Grip ( $p = .00068$ ) and that No Biofeedback is different from Biofeedback DF with Grounded Grip ( $p = .033$ ) however, Biofeedback DF is not different from Biofeedback DC with Grounded Grip ( $p = .369$ ).

Pairwise comparisons between No Biofeedback, Biofeedback DC and Biofeedback DF for Air Grip : Pairwise comparisons show that No feedback is not different from Biofeedback DC for Air Grip ( $p > .99$ ), that No Biofeedback is not different from Biofeedback DF for Air Grip ( $p = .243$ ) and that Biofeedback DF is not different from Biofeedback DC for Air Grip ( $p > .99$ ).

## 9 Details of the 2-way rm Anova on the Amount of Biofeedback Received

A two-way repeated measures ANOVA was performed to evaluate the effects of Biofeedback and Grip on the amount of vibration received by the participant. The statistical analysis shows an effect of Biofeedback on the amount of vibration received.

Main Effects and Interactions : A **significant main effect of Biofeedback** was found ( $F(1, 13) = 118.441, p < .0001, \eta^2 = .354$ ). However, no significant interaction between Grip and Biofeedback was found ( $F(1, 13) = .064, p = .805, \eta^2 < .001$ ) nor an effect of Grip ( $F(1, 13) = 1.937, p = .187, \eta^2 = .043$ ).

Pairwise comparisons between Biofeedback DC and Biofeedback DF for Air Grip and Grounded Grip : Pairwise comparisons show that Biofeedback DF is different from Biofeedback DC with Air Grip and Grounded Grip ( $p < .0001$ ).

## Annexe D

# The Phantom Sensation : A Tactile Illusion of Motion

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## 1 Introduction

The tactile modality is widely used in human machine interfaces as it is an easy and safe way to convey information without hindering the other senses.

Conveying tactile information can be based on tactile illusions of motion, which have been studied since the beginning of the last century ([Burtt, 1917](#)). A tactile illusion is usually described as a discrepancy between the expected perception of a physical stimulus and the real perception, that is usually surprising and perplexing (Scholarpedia on tactile illusions).

[Burtt \(1917\)](#) found that, under some conditions of intensity, spacing and time, participants could perceive a motion between two tactile stimuli. Whether the perceived motion is discrete (the rabbit illusion ([Geldard & Sherrick, 1972](#); [Sherrick & Rogers, 1966](#)) or continuous (the phantom sensation ([Alles, 1970](#))), it can convey an information of direction ([Luces, Okabe, Murao, & Hirata, 2018](#)).

During Phantom Sensations (PS), spatiotemporal interactions are at play. [Alles \(1970\)](#) suggests that the PS may arise from a combination of temporal and amplitude inhibitions. First, he explains that two stimuli of equal amplitude, occurring subsequently with a short time delay will be perceived as one stimulus. The perceived position depends on the time delay, often called Inter-Stimuli-Onset-Interval (ISOI) ([Gardner &](#)



[Sklar, 1994](#)). Then, he explains that two stimuli of varying amplitude are perceived as a motion between them. The perceived position is hence modified by a change of amplitude through time. In short, there is a close relationship between the perception of distance and time ([Cholewiak, 1999](#)).

[Berger et Gonzalez-Franco \(2018\)](#) explain in that the perceived area of stimulation is not always at the location of the physical contact with the skin. In their experiment, participants were holding two handles, one in each hand, while seeing their hands only holding a single object through a Virtual Reality Display. Participants felt a motion going from one hand to the other. Other experiments confirm that a tactile stimulation can be perceived out of the body between the stimulated parts of the body ([Berger & Gonzalez-Franco, 2018](#) ; [Eimer & Forster, 2005](#) ; [Miyazaki, Hirashima, & Nozaki, 2010](#)). [Miyazaki et al. \(2010\)](#) explain in this mislocalisation outside of the body by saying that the object is added to the mental scheme of the body. In all these studies on the mislocalisation, the end-point of the illusion never goes beyond the area defined by the actuators.

The PS described in ([Alles, 1970](#)) is an interesting case of spatiotemporal interaction. Moreover, this illusion is reported to have a good direction detection success rate. It could be more useful in applications such as assistance, rehabilitation or virtual reality systems if the perceived end-point of the movement could be controlled.

However, [Alles \(1970\)](#) found that depending on the displayed PS, the end-point of the PS cannot be perceived easily, if not at all, by participants. This comment by [Alles \(1970\)](#) was the start point of our study on the perception of the end-point of PS illusions.

We conducted a first investigation of the perception of the end-point of a PS. We studied the influence of the duration of the stimulation on the perceived distance travelled by the illusion. The perceived distance was evaluated by investigating the influence of the duration on the perceived position of the end-point of the motion. We questioned whether the end-point of a PS could be perceived out of the hand or even outside of the object held.

A second study was conducted. The aim of the study was to investigate more precisely the position of the perceived end-point to extract a relationship between the duration of the illusion and the position of the end-point.

The first study is detailed first. The second study is presented afterwards.

## 2 The First Study : Out of Hand and Out of Object Perception

This study was published at the World Haptics Conference 2019 under the name "Phantom Sensation : When the Phantom escapes the bounds of the actuator and the end-point is sensed in the air" in (Bellicha, Trujillo-León, & Bachta, 2019).

Three experiments have been conducted. The experiment 1 "Discrimination of the direction" shows that the direction detection is independent of the stimulation duration. The experiment 2 "Out of hand detection" shows that the end-point of the PS can be perceived out of the hand palm. The experiment 3 "Out of object detection" shows that the end-point could even be perceived out of a grasped object, in the air.

To this end, two custom handles of different lengths were used. Both handles are fitted with two actuators each. The distance inter-actuator is the same for the two handles and approximately equal to an average hand palm width. The duration of the PS was varied, but the maximal amplitude of stimulation was the same across durations.

In this paper, we show that a tactile stimulation can be perceived out of the hand, in the object or in the air beyond the object which is beyond the stimulators positions. These mislocalisations seem related to the duration of the tactile illusions.

### 2.1 Material and Methods

#### 2.1.1 Experimental setup

The experimental setup is based on two custom handles of different lengths. The long handle (345 mm long) is depicted in Figure 1A. The short handle (of 143 mm long) is in Figure 1B.

Both handles consist in a T-shape support composed of equal halves, spaced by 1 mm. Two actuators vibrating tangentially are embedded into each half, using silicon material. Spacing and the use of silicon are meant to reduce interferences between the actuators. The actuators are placed 7 cm apart. This distance corresponds roughly to the mean width of a hand palm. The actuators have been built based on the recommendation of Yao (2011). They are replicable.

The long handle is meant to help us determine whether an out of hand end-point perception is possible.

The short handle was designed to see whether an out of object end-point perception is possible. Its length has been defined carefully. The length was chosen to be comfortably grasped, and to prevent participants from determining its length during the experiment.

The experimental setup schematized in Figure 2 explains the driving of the actuators of both handles.

The setup works as follows : MATLAB is used to generate the two signals that drive the vibrotactile actuators creating the tactile illusion. Outputs of the NI USB6001 card, running at a 2 kHz rate are finally passed through audio-amplifiers before being sent to the actuators.

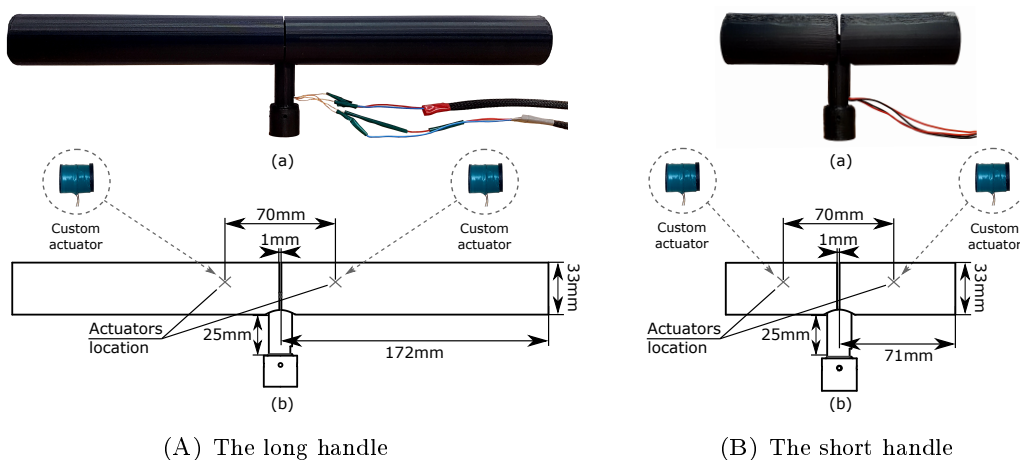


FIGURE 1: Pictures of the long and short handles in (A)(a) and (B)(a) and sagittal sections of the long and short handles in (A)(b) and (B)(b).

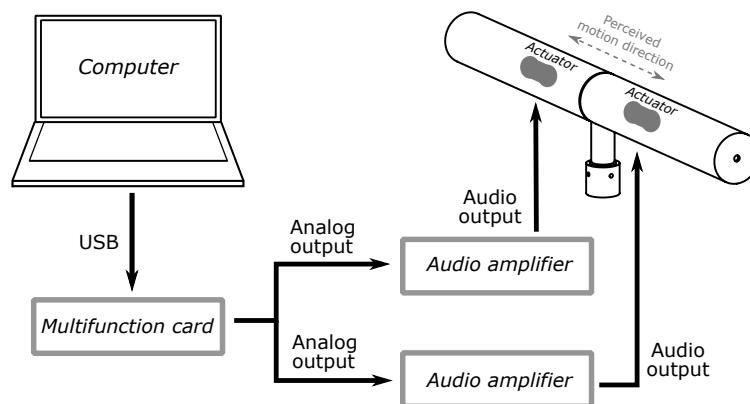


FIGURE 2: Experimental setup scheme.

For experiments 2 and 3, 2 sheets of paper were used. The drawing in Figure 3(a) is the participant sheet. It represents the long handle. The gray area represents their grasp on the handle. The drawing shown in Figure 3(b) is the experimenter sheet. The drawing is divided into 9 areas. Area 0 is the central area corresponding to the grasp and

the position of the actuators. The rest of the drawing is divided equally into 3 areas on each side of area 0. Areas numbered 4 refer to an end-point out of the long handle. It is worth noting that the short handle length corresponds to area 0 and both areas denoted 1. The direction and the number of the area pointed by the participant is recorded.

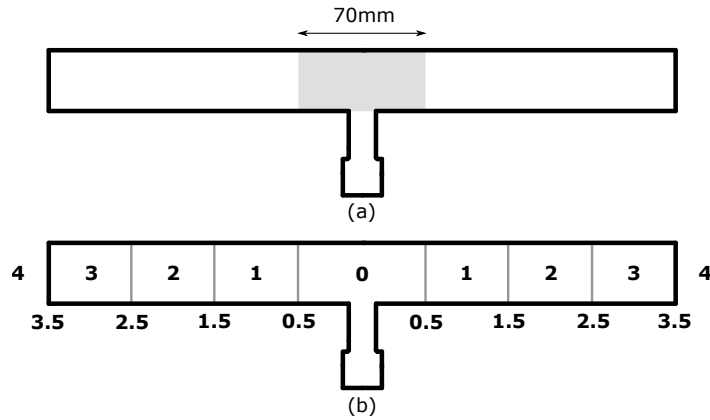


FIGURE 3: (a) Drawing showed to the participants. The gray area represents the hand palm contact. (b) Drawing used by the experimenter.

### 2.1.2 Stimuli

First, the actuators of both handles were tuned to provide equal intensity.

Tactile stimuli corresponding to the PS as described in (Alles, 1970) were synthesized. Seven PS durations were chosen :  $\{ 0.25, 0.5, 0.75, 1, 1.5, 2 \text{ and } 2.5s\}$ . In total, 14 PS were synthesized, with seven different durations for each direction (forward or backward).

As explained in (Alles, 1970), the envelope of the two signals of a PS must not be linear as it would be detrimental to the illusion as the total perceived amplitude of the two signals would not be constant.

Here, the chosen envelope for all the signals, is an arc-tangent function. This function is like the logarithmic function and gives a reliable illusion. All envelopes were normalized in order to have the same maximal amplitude across all durations. The carrier signal is a sawtooth signal of  $80Hz$ . It was chosen to provide a well perceived illusion.

An example of a stimulus showing the two signals used to drive the two actuators for the 0.25s duration is shown in Figure 4. One should notice that the envelope of the shown signal, chosen to clearly expose the carrier signal, has also an arc-tangent envelope. Its shape looks linear due to its short duration.

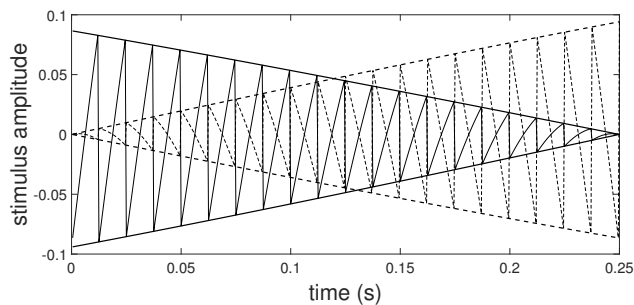


FIGURE 4: Example of a signal generated. This signal was used for the phantom sensation of a duration of 0.25s. The full lines represent the signal generated and sent to the actuator 1 (envelope and carrier signal) and the dashed lines represent the signal generated and sent to the actuator 2 (envelope and carrier signal). The envelope is an arc-tangent function.

### 2.1.3 Participants

**Experiments 1 and 2** 12 subjects (ten male, two female, with ages ranging from 23 to 28 years old) participated voluntarily in experiments 1 and 2.

**Experiment 3** Five subjects (three male, two female, with ages ranging from 24 to 29 years old) participated voluntarily in experiment 3.

None of the participants who took part in the experiment reported any motor, sensory or neurological disorders. They were unaware of the aim of the study, and had given their informed written consent.

### 2.1.4 Experiments and testing conditions

Subjects sat comfortably and held the handle horizontally by the middle with their right hand. The handle was maintained along their sagittal plane. Subjects wore headphones with pink noise and closed their eyes during the experiment to avoid any inter-modality bias. The lights in the experimental room were dimmed. They received no feedback during the experiments. At the end of the experiments, an informal discussion took place with each participant to record their general impressions. These impressions concerned the clarity of the information, the perceived speed of the motion and whether they felt a relationship between the duration of the illusion and the distance travelled or any comment they thought relevant. Each experiment lasted approximately 20 minutes.

**Experiment 1 - Discrimination of the direction** It was conducted in order to check if the duration influences the direction detection. In this experiment, the long handle has been used. In order to avoid fatigue, only three durations have been tested : the shortest (0.25 s), the longest(2.5 s) and one in-between (1 s).

A two-alternative forced choice protocol was used to validate the discrimination of the direction of the PS. For each duration, pairs of forward/backward, backward/forward, forward/forward, and backward/backward have been prepared. This makes a total of 4 pairs for each duration, hence 12 pairs for all the tested durations. Each pair was repeated 5 times in a randomized order leading to a total of 60 pairs of signals per participant. For each pair of signals presented, the subject was asked to report which signal was going forward. The answer was recorded. The experiment 1 lasted approximately 20 minutes.

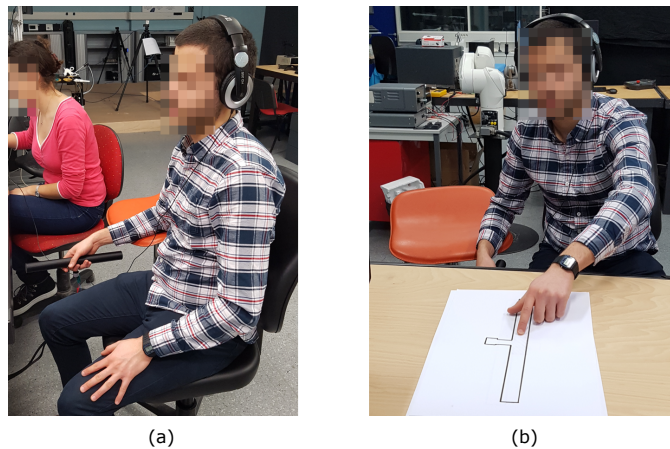


FIGURE 5: Participant performing the (a) Experiment 1 (b) Experiment 2 or 3.

**Experiment 2 - Out of hand detection** In this experiment, the long handle was used. Participants saw the handle. The drawing placed in front of them is shown in Figure 3(a). As explained in section 2.1.1, the drawing is a 1 : 1 representation of the long handle. It was explained to the participants that the gray area represented their grasp on the handle.

Participants were presented stimuli and informed of their direction and were asked for each to locate the end of the movement on the sheet of paper in front of them. After each stimulus, the participant answer was recorded by the experimenter using the areas presented in section 2.1.1 and shown in Figure 3(b). The direction of motion has also been recorded.

Each of the 14 stimuli described in section 2.1.2 was presented five times in a random order leading to 70 randomized trials separated by rest periods.

**Experiment 3 - Out of object detection** In this experiment, the short handle was used although the drawing used in experiment 2 was presented to the participants. Participants did not see the handle. This experiment was conducted to test whether the end-point could be out of the handle. The difference between the drawing and the object was chosen in order to avoid biasing participants into choosing an end-point in the handle.

Otherwise, the experimental procedure was the same as in Experiment 2.

## 2.2 Data recording, analysis and results

The data collected during our experiments did not have a normal distribution. For this reason, medians and inter-quartile ranges were used to represent them. Non-parametric tests were also used for the statistical analyses.

**Experiment 1 - Discrimination of the direction** Figure 6 shows a box plot of the direction detection probability. 1 and 0 represent, respectively, the probability of detection of the direction 100% and 0% of the time. In this plot, all data from all participants are pooled together. A Friedmann test showed that there is no significant difference between the three durations ( $p > 0.05$ ).

The duration does not significantly affect the probability of direction detection of a PS.

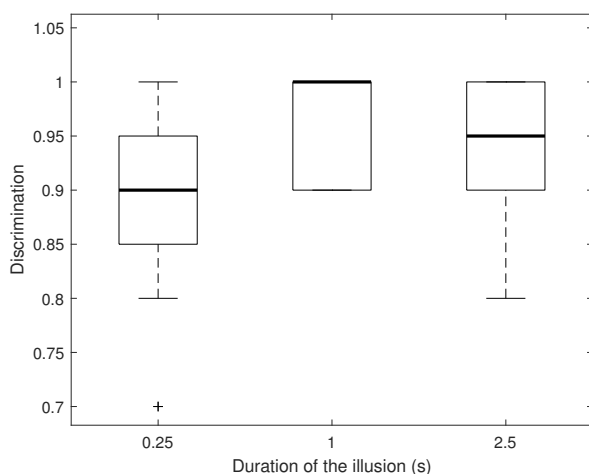


FIGURE 6: Experiment 1 - Boxplot of the probability of discrimination of the direction depending on the duration of the illusion. The diagram shows the median observation. The lower and upper quartiles are also represented. Data falling outside the interquartile range are plotted as outliers of the data.

**Experiment 2 - Out of hand detection** As explained in section 3.1.4, after the pointing of the participant on the sheet depicted in Figure 3(a), the experimenter records the given answer based on the drawing presented in Figure 3(b), as well as the direction of the motion.

Area boundaries (0.5, 1.5, 2.5 and 3.5) have been used to facilitate the data collection. To simplify the analysis, these boundaries have been merged with the adjacent area. The forward and backward directions have been also pooled together.

Data have been separated into three groups :

- Participants who perceived the end-point of the stimulation both in and out of their hand. This group comprises seven out of twelve participants.
- Participants who perceived the end-point of the stimulation mostly or only in their hand (only the areas number 0 and 0.5 are reported). This group comprises three out of twelve participants.
- Participants who perceived the end-point of the stimulation mostly or only out of their hand (only areas 1 or bigger are reported). This group comprises two out of twelve participants.

For each group, a psychometric curve was fitted to the data. For the first group, the psychometric curve is drawn in Figure 7A. For the two other groups the curves are drawn in Figure 7B. The point of out of hand perception,  $\mu$ , is the duration at which the psychometric curve crosses a probability of 0.5. For the first group, reporting in and out of hand perception,  $\mu = 0.77s$ .



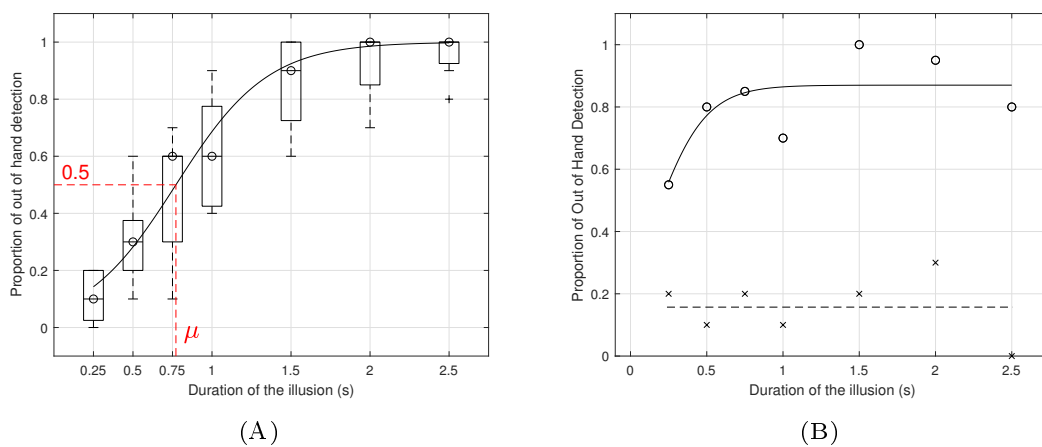


FIGURE 7: Experiment 2 : Psychometric curve of the detection of the ending of the movement out of the hand as a function of the duration of the illusion. Areas 0.5, 1.5, 2.5 and 3.5 were grouped with areas 0, 1, 2 and 3 respectively. The two directions were treated together. Psychometric curves (A) for all participants who perceived in and out of hand movement, represented with boxplots, were used to compute this psychometric curve. The point of out-of-hand perception  $\mu = 0.77s$  is plotted. (B) for all participants who perceived mostly in or mostly out of hand movement. The full line and 'o' correspond to out of hand participants. The dashed line and 'x' correspond to in hand participants.

Figure 8 represents a heat map of the percentage of detection in an area depending on the duration. As explained, the hand corresponds to the area 0 of the drawing hence a detection in the area 1 or above is not in the hand. It was computed for all participants of the three groups pooled together. The heat map seems to suggest that there is a relationship between the duration and the perceived area containing the end-point of the movement.

The end-point of the movement was perceived 67% of the time out of the hand. The end-point of the movement was perceived 48% of the time in the areas marked 1. These areas are close to the hand but out of the grasp.

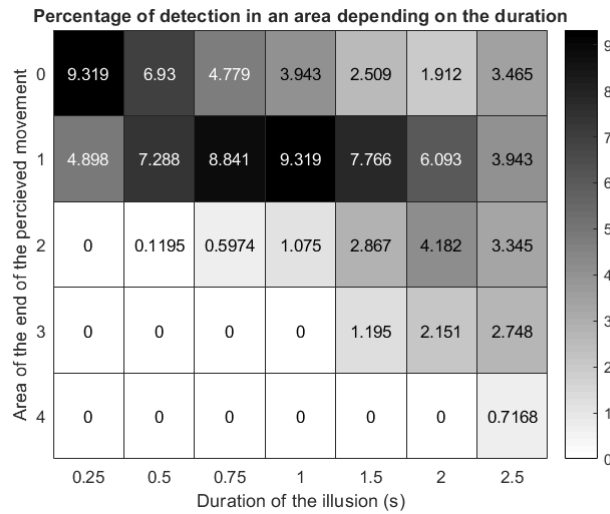


FIGURE 8: Experiment 2 - heatmap of the percentage of detection in an area depending on the duration for all participants. Areas 0.5, 1.5, 2.5 and 3.5 were grouped with Areas 0, 1, 2 and 3 respectively. The two directions were treated together.

**Experiment 3 - Out of object detection** One subject out of five was discarded because the participant explained after the experiment that his/her answers were not based on the perceived area but rather on a mental correspondence between the size of the drawing and the used handle.

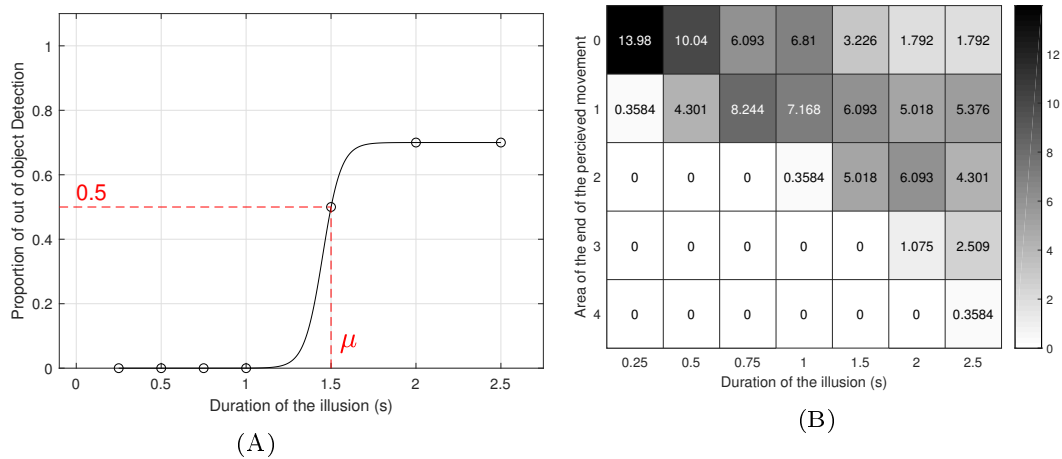


FIGURE 9: Experiment 3 : (A) Psychometric curve of the detection of the end-point of the movement out of the object as a function of the duration of the illusion. The median of the data of the four retained participants were used to compute this curve. The two directions were treated together. The 'o' corresponds to the median values. The point of out of object perception  $\mu = 1.5s$  is plotted. (B) Percentage of detection in an area depending on the duration for the four retained participants. Areas 0.5, 1.5, 2.5 and 3.5 were grouped with Areas 0, 1, 2 and 3 respectively. The two directions were treated together.

Figure 9A shows the psychometric curve for the answers pooled across the four retained participants. The point of out of object perception,  $\mu$ , is the duration at which the psychometric curve crosses a probability of 0.5,  $\mu = 1.5s$  for out of object perception.

Figure 9B represents the heatmap of the percentage of detection in an area depending on the duration. It was computed for the retained participants. As explained, the handle size corresponds to the areas 0, and both 1. Hence a detection in the area 2 or above is considered out of the handle.

Participants' answers have been processed like in Experiment 2.

Inspection of the heatmap seems to suggest that there is a relationship between the duration and the perceived area containing the end-point of the movement.

The end-point of the movement was perceived almost 20% of the time out of the hand. It was perceived 16% of the time in the areas 2. These areas are close to the handle but out of it.

## 2.3 Discussion

Experiment 1 shows that the duration has no effect on direction discrimination for durations between 0.25 and 2.5s.

Experiment 2 shows that if the duration of the PS is greater than  $\mu = 0.77s$ , then the end-point of the motion is perceived out of the hand, in the handle.

Experiment 3 shows that if the duration of the PS is greater than  $\mu = 1.5s$ , then the end-point of the motion is perceived out of the handle, in the air.

Experiment 2 shows that for some participants, the end of the motion is either always in the hand or always out of the hand.

### 2.3.1 Mechanisms likely responsible for the out of hand and out of object perception

Participants perceived the end-point of the PS out of their hand or out of the object depending on the duration. A likely explanation of this perception relies on the process of the evaluation of distance and motion. This process is a combination of different factors. First, personal experiences are accumulated through all our contact with moving objects (Nguyen, Taylor, Brooks, & Seizova-Cajic, 2015). Secondly, our perception may be described as a weighted average of spatial and temporal judgments. This accumulation

forms what is called a "natural context" of perception of distance and motion (Jones & Huang, 1982). PS is a case of spatiotemporal interaction that seems to fit in the model described by Nguyen et al. (2015) and Jones et Huang (1982). An increased duration in a constant-velocity movement will be perceived as an increased distance travelled in this "natural context". The heatmaps presented show a likely relation between the duration and the end-point position. The duration  $\mu$  from which the end-point is out of the hand is shorter than the duration  $\mu$  from which the end-point is out of the handle. These results support the idea that a bigger duration is perceived as a bigger travelled distance in a constant velocity context. Perception of distance is also not only based on the sensory information but on the mental scheme of one's body in the world (Badde & Heed, 2016). The handle is probably added to the body mental scheme (Miyazaki et al., 2010; Salemmé et al., 2018), resulting in a possible perception out of the hand/handle. Participants also felt out of handle end-points. Out of the handle end-points may have been in the continuity of the movement and not rejected because the handle was hidden making the felt position more likely.

### 2.3.2 Mechanisms likely responsible for the only in hand perception

Some participants (three out of the 12) of the experiment 2 felt only in hand end-points. They all explained in the post-experiment discussion that they felt different speeds of motion. They explained that the longer the durations, the slower they were perceived. In the same way, shorter durations were perceived as faster. It is thus likely that a long duration was not perceived as a long distance since they perceived a change of speed of motion. Nguyen et al. (2015) explain that localisation depends on velocity perception. They also explain that a "compressive mislocalisation" is possible and depends on the velocity. This "compressive mislocalisation" would appear here as only in hand perception.

### 2.3.3 Mechanisms likely responsible for the out of hand perception

Two participants out of the 12 of the experiment 2 felt only out of hand perception and rarely felt the end-point in their hand. The psychometric curve of out of hand detection as a function of duration is not constant. It is possible that those participants overestimated the travelled distance with out of hand end-points as a result.

### 2.3.4 Some of the study limits

A tactile interface to record the exact position of the end-point of the movement could have been used. Besides, increasing the number of participants should make our observations more reliable. In this study we did not take into account the direction of motion. In (Nguyen et al., 2015), it is reported that there is a difference of distance perception depending on the direction. Therefore, we should reprocess our data as a function of the direction of the PS.

## 2.4 Conclusion

This study shows that an increase in duration of a Phantom Sensation results in a perceived end-point of the motion out of the hand or out of the object. Furthermore, the results suggest that a Phantom Sensation depending on its duration is not bound by the position of the actuators.

## 3 The second study : A closer look at the relationship between the duration and position of the perceived end-point.

As explained in the section above, the position of the perceived end-point was not recorded precisely and the number of participants was quite small given the variability intra-participants.

For this second study, two experiments have been conducted in order to study the relationship between the duration of the illusion and the position of the perceived end-point. The experiment 1 "Discrimination of the direction" shows that the direction detection is independent of the stimulation duration. The experiment 2 "End-point positions as a function of duration" shows that the perceived end-point position depends on the duration of the illusion and that the end-point of the PS can be perceived out of the hand palm.

Only the short handle was used. Like in the first experiment, the handle is fitted with two actuators each. The distance inter-actuator is approximately equal to an average hand palm width. The duration of the PS was varied, but the maximal amplitude of stimulation was the same across durations. A tactile screen was used to precisely record the perceived position of the end-point.

In this experiment, the directions forward/backward were switched to leftward/rightward for practical reasons.

### 3.1 Material and Methods

#### 3.1.1 Experimental Setup

The experimental setup is based on one custom handle. The handle used is the short handle presented in the first study. The short handle (of 143 mm long) is in Figure 1B.

The handle, as explained for the first study consists in a T-shape support composed of equal halves, spaced by 1 mm. Two actuators vibrating tangentially are embedded into each half, using silicon material. Spacing and the use of silicon are meant to reduce interferences between the actuators. The actuators are placed 7 cm apart. This distance corresponds roughly to the mean width of a hand palm. As explained in the first study description, the length was chosen to be comfortably grasped, and to prevent participants from determining its length during the experiment.

The experimental setup schematized in Figure 2 explains the driving of the actuators of both handles.

For the experiment 2, a 24in tactile screen was used. The drawing in Figure 10 was displayed on the tactile screen in front of the participant.



FIGURE 10: Drawing displayed on the screen for the experiment 2. The gray zone represents the grasp of the participant.

The gray area represents their grasp on the handle with a scale of 1 :1. As the size of the handle was unknown, the rest of the handle was represented with dashed lines. The difference between the drawing and the object was chosen in order to avoid biasing participants. We chose to use dashed lines instead of the representation of a bigger object,

this kind of representation could induce a bias. If participants always perceive end-points close to the hand or only in it, the representation of a big object might bias them into choosing positions further than the originally perceived ones. The position touched by the participant was recorded.

### 3.1.2 Stimuli

The stimuli used for the second experiment are the same as the ones used in the first study. The 7 durations are :{ 0.25, 0.5, 0.75, 1, 1.5, 2 and 2.5s} In total, 14 PS were synthesized, with seven different durations for each direction (leftward or rightward).

For reasons explained in the section 2.1.2 of the first study, the chosen envelope for all the signals, is an arc-tangent function. This function is like the logarithmic function and gives a reliable illusion. All envelopes were normalized in order to have the same maximal amplitude across all durations. The carrier signal is a sawtooth signal of  $80Hz$ . It was chosen to provide a well perceived illusion.

An example of a stimulus showing the two signals used to drive the two actuators for the 0.25s duration is shown in Figure 4. As for the first study, the vibrotactile actuators of both handles were tuned to provide equal intensity.

### 3.1.3 Participants

15 subjects (10 male, 5 female, with ages ranging from 22 to 26 years old) participated voluntarily. None of the participants who took part in the experiment reported any motor, sensory or neurological disorders. They were unaware of the aim of the study, and had given their informed written consent.

### 3.1.4 Experiments and Testing Conditions

Subjects sat comfortably and held the handle horizontally by the middle with their dominant hand. The handle was maintained along their frontal plane. Subjects wore headphones with pink noise and closed their eyes during the experiment to avoid any inter-modality bias. The lights in the experimental room were dimmed. They received no feedback during the experiments. At the end of the experiments, an informal discussion took place with each participant to record their general impressions. These impressions concerned the clarity of the information, the perceived speed of the motion and whether they felt a relationship between the duration of the illusion and the distance travelled or any comment they thought relevant. Each experiment lasted approximately 20 minutes.

**Experiment 1 - Discrimination of the direction** It was conducted in order to check if the duration influences the direction detection. This experiment is very similar to the one conducted in the first study. Unlike for the first study, the short handle was used, forward/backward directions were switched to leftward/rightward and participants answered using a graphical interface by clicking on the screen. Only three durations have been tested : the shortest (0.25 s), the longest(2.5 s) and one in-between (1 s).

A two-alternative forced choice protocol was used to validate the discrimination of the direction of the PS. For each duration, pairs of leftward/rightward, rightward/leftward, leftward/leftward, and rightward/rightward have been prepared. This makes a total of 4 pairs for each duration, hence 12 pairs for all the tested durations. Each pair was repeated 5 times in a randomized order leading to a total of 60 pairs of signals per participant. For each pair of signals presented, the subject was asked to report which signal was going to the right. The answer was recorded. The experiment 1 lasted approximately 20 minutes.

**Experiment 2 - End-point positions as a function of duration** A photo of a right-handed participant performing the second experiment can be seen in Figure 11.

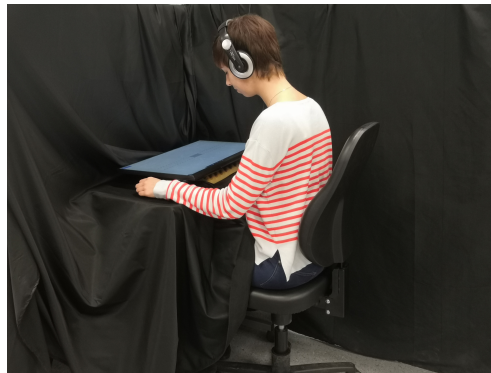


FIGURE 11: Participant performing the Experiment 2.

As in the third experiment of the first study, participants did not see the handle. The drawing displayed on the screen placed in front of them is shown in Figure 10. As explained in section 2.1.1, the drawing is a 1 : 1 representation of the grasp of the participant. It was explained to the participants that the gray area represented their grasp on the handle. They were informed that they could click anywhere they wanted on the screen.

Participants were presented stimuli and informed of their direction and were asked for each to locate the end of the movement by touching the position on the screen. After each stimulus, the participant answer was recorded.



Each of the 14 stimuli described in 2.1.2 was presented five times in a random order leading to 70 randomized trials separated by rest periods.

### 3.2 Data Recording, Analysis and Results

**Experiment 1 - Discrimination of the direction** Figure 12 shows a barplot of the direction detection probability. 1 and 0 represent, respectively, the probability of detection of the direction 100% and 0% of the time. In this plot, all data from all participants are pooled together. A 1-way ANOVA showed that there is no significant difference between the three durations ( $p = .72$ ). A parametric test was test as the normality hypothesis was not rejected. The duration does not significantly affect the probability of direction detection of a PS.

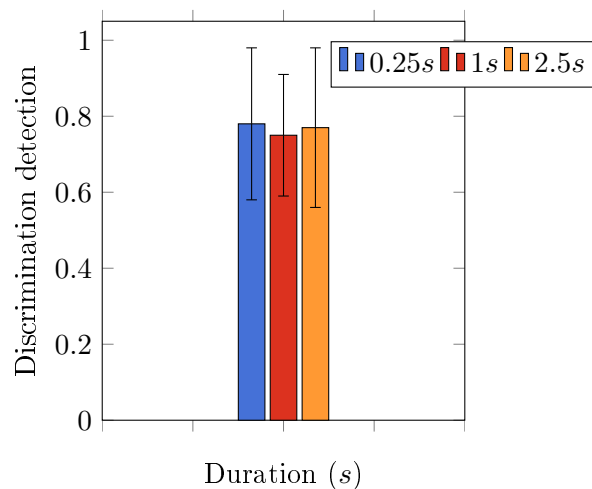


FIGURE 12: Experiment 1 - Boxplot of the probability of discrimination of the direction depending on the duration of the illusion.

**Experiment 2 - End-point positions as a function of duration** The results of three participants out of 15 were excluded from the analysis as they had information concerning the size of the object. They either saw the object or grasped the end of the handle.

**Relationship between the position of the end-point and the duration** Figure 13 shows the mean position in mm of the perceived end-point for each duration with the standard deviation associated for each direction.

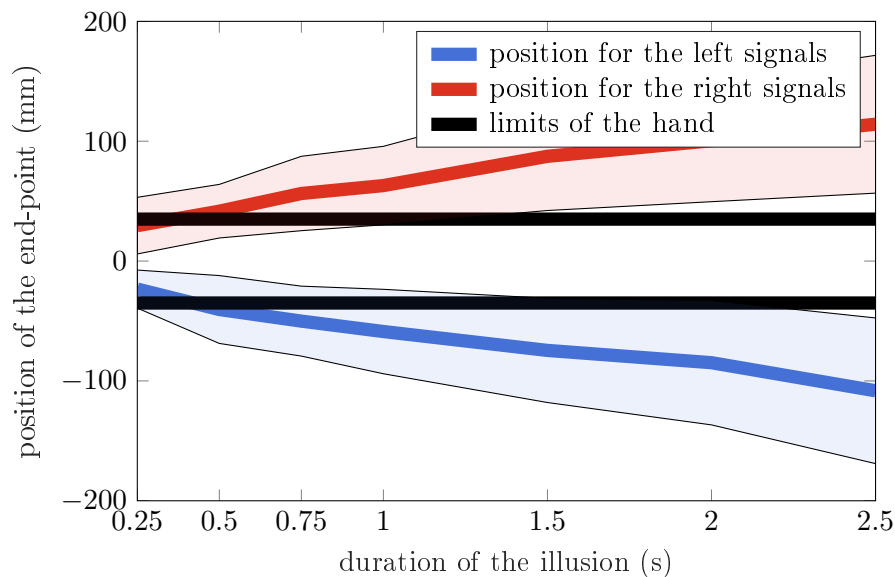


FIGURE 13: Position of the perceived end-point as a function of duration of the illusion. The mean position is drawn in full lines and the standard deviation is shown using transparent areas. Perceived end-points of leftward illusory motions are drawn in blue and are measured with negative distances while perceived end-points of rightward illusory motions are drawn in red and are measured with positive distances.

We can clearly see that position is increasing in amplitude with the duration and that most positions in mean are out of the hand. The increase seems similar for both directions. The standard deviation in light blue and light red shows that some end-points are perceived close or in the hand.

The correlation between the position and the duration was computed for each direction using *R* software. The position and the duration are significantly correlated for

- illusions to the left :  $p < .001$  and  $\rho = 0.56$  ;
- illusions to the right :  $p < .001$  and  $\rho = 0.60$ .

The relationship between the duration and the position can be computed with a linear regression for the two directions (left and right). The equations are written below with  $t$  the time in seconds and  $pos$  the position of the end-point in millimetre.

$$pos_{left} = 35 * t + 21 \tag{D.1}$$

$$pos_{right} = 38 * t + 25 \tag{D.2}$$

**Out of hand perception** The positions were mostly out of the hand as it can be seen on Figure 13.

The probability of out of hand detection for each duration was computed for each participant and for each direction.

Figure 14 shows the probability of preception of the position out of the hand for each participant as a function of the duration. While some participants perceived the end-point always or almost always out of the hand (participants 4, 5, 7, 11, 12), other perceived them always or amost always in the hand (participants 1, 2 and 6). Apart from participants 8 or perhaps 10, there was not a progressive perception going from inside the hand to outside the hand.

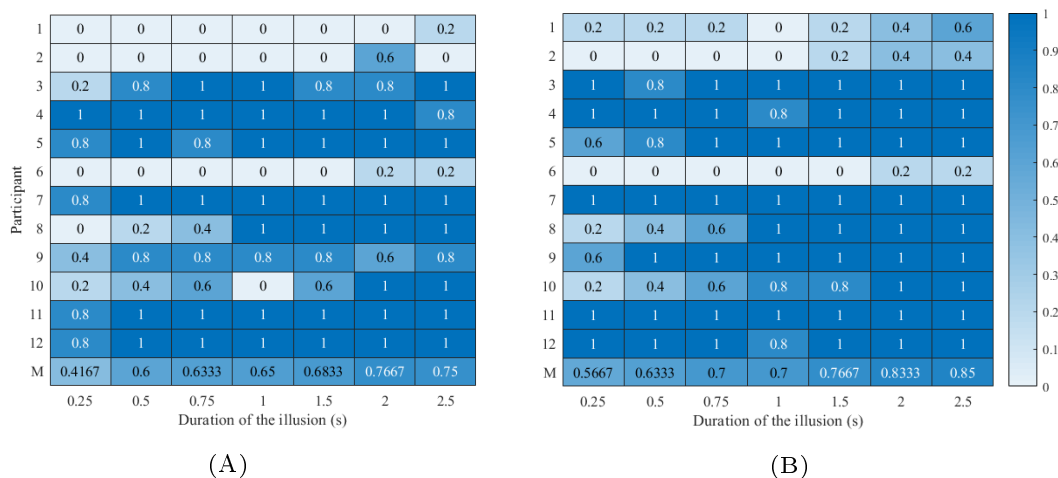


FIGURE 14: Out of hand perception as a function of duration for each participant with the Mean (M) across participants. A value of 1 indicates a 100% out of hand perception and 0 indicated a 0% out of hand perception.

The end-point was outside the hand for 64% of stimulations for the left and 70% for the right direction. This percentage was obtained by dividing the number of cells with a probability of out of hand detection greater than 0.5 over the number of cells.

Probability for the end-point to be out of the hand greater than 0.5 is found in average for a duration greater of equal to 0.5s for the left and 0.25s for the right direction. In average, the probability is increasing with an increase of time.

We did not draw the psychometric curves of out of hand detection like in the first study given the data over participants.

### **3.3 Discussion**

Experiment 1 shows that the duration has no significant effect on direction discrimination for durations between 0.25 and 2.5s (0.25, 1 and 2.5x).

Experiment 2 shows that there is a correlation between the duration and the position of the perceived end-point of the motion. The greater the duration, the greater the amplitude of the position.

Experiment 2 shows that most stimulations were felt out of the hand and that for several participants, the end-point was always out of the hand.

Contrary to the first experiment, there was little to no progression between in hand to out of hand for most participants.

It was not quantified but most participants reported at the end of the experiment that the detection of the direction and of the end-point required a lot of focus.

#### **3.3.1 Mechanisms explaining the relationship between the duration and the position**

This relationship was discussed in [2.3.1](#)

For both studies, the duration for out of hand perception is quite low, inferior to 1s. This is lower than values usually found in the literature. These differences are maybe due to the use of a sawtooth signal and not a sinusoidal signal for the carrier signal. It is possible that the sawtooth signal is adding to the effect of motion due to its asymmetry. The friction is different for a sawtooth signal than a sinusoid ([Popov, 2020](#)). This difference may be enhanced the perception of motion.

#### **3.3.2 Discussion of the differences of the results of the two experiments**

The differences between the results of the first and second study raise several questions. The differences in methods are the following :

- the interface used by the participants to locate the end-point
- different participants
- the direction forward/backward for the first study were switched to leftward/rightward.
- in the Experiment 2 used to assess in and out of hand perception, the participants saw the object.

## 4 Conclusion

The influence of the duration of the illusion on the position of the end-point and its localisation outside of the hand and/or object has been investigated. We found that the position of the perceived end-point was correlated with the duration of the illusion. We also found that the end-point could be localized out of the hand and even out of the object hence beyond the positions of the actuators. However, the variability in results across participants suggest that further investigation is necessary.

We would like to question whether the relationship between the duration and the position is the result of the perception of the participants or if they possibly decided that it was likely that the appropriate answer to our experiment was to link the duration and the distance.

