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Internship report

Human Perception of Spatial Orientation and Motion

Technicolor
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Internship context

The use of physical stimulations is still very limited in man-machine technologies. If vibration cues have become usual with the development of smartphones and tablets, they are still limited to quite basic content, like confirmation or alarm signals. There is clearly a large scope of improvements in using the physical modalities and combining them with existing audiovisual techniques, in order to take significant steps towards better ergonomy or immersivity.

Technicolor is a world leader in multimedia related services and technologies, supporting broad research and development efforts in related fields. Inside the Media Computing Laboratory, new interfaces and future man-machine technologies are studied and developed as they are expected to play a key role in multimedia consumption in the years to come.

What if we could enhance multimedia content with physical sensations ?

Audiovisual technologies have gone through considerable development over last decades and their performances are constantly increasing. But no matter their quality and sophistication, they can't help a lack of body sensations, because other modalities have to be used to produce bodily effects efficiently.

The most obvious way to produce global motion sensation is of course to really move the whole body (like in flight simulators or so-called 4D cinemas), but the energy needed by such devices makes them massive and expensive. Another approach is to produce the sensation of movement instead the “real” movement itself, i.e. create an illusion. Although perceptual illusions are often limited to a certain context, they generally need only a very light and elegant setup, which is an important criteria for virtual reality applications for instance. However this topic is still underexplored and little is known about motion perception limits and possibilities, except that its complexity reserves, for sure, many surprises.

The goal of this “exploratory” internship is to pursue the research activities on haptic feedback and motion perception done in Technicolor and more specifically, to evaluate how different stimulations may or may not create illusion of motion or displacement in the space.

Detailed summary

Introduction

The perception of body orientation and motion is a complex and multimodal mechanism. If the vestibular system is the main organ for perceiving motion, the body spatial configuration is also used and is mainly based on cues from mechanoreceptors distributed throughout the body.

These mechanoreceptors may therefore be physically stimulated to alter the body perception and artificially induce either reflex body responses or virtual motion sensations (called kinesthetic illusions).

However, these two body perceptions (motion and configuration) are strongly influenced by other sensory systems like vision or even audition, and also by cognitive factors. Numerous experimental results suggest that such these perceptions arise from the combination of different sensory informations, but very little is known about the exact modalities of this sensory integration, and no global model has been proposed so far.

Thus, altering these perceptions in a precise and reproducible way means meet the challenge of handling a complex combination of many factors. This internship aimed a better understanding of these perceptual mechanisms, in order to identify possibilities of producing artificial motion sensations.

A state of the art was established on self-motion perception mechanisms and on existing kinesthetic illusion techniques in the literature, but also on the corresponding actuator technologies. Then, a technique was chosen to be experimentally evaluated with a psychophysics experiment.

I. Proprioception and psychophysics terminology

1) Introduction

The question of vocabulary is major issue in the transdisciplinary field of perceptions : the core terms and definitions are rarely totally clear and often vary according to authors. Most concepts, even the most key ones, seem to be still debatable depending on the chosen point of view, despite decades of discussions.

In this first part, I will thus briefly propose definitions and descriptions, summarized in Fig. 1, that seem to me to be the most coherent and to fit the best the numerous publications I read during my bibliography.

Proprioception refers to the perception of our own body. It includes several distinct sensory systems : the vestibular system, the tactile sense and the kinesthetic sense. Each of those has its own biomechanical receptors. The vestibular system is responsible for head and global motion detection, whereas the kinesthetic sense perceives limb movements and positioning. Tactile sense is about cutaneous sensations and includes touch, temperature and pain informations.

Tactile and kinesthetic senses are sometimes referred together as the somatosensory (or somesthetic) system.

Proprioception is opposed to exteroception, which defines the perception of the outside of our body. Vision and hearing, for instance, belong to exteroception.

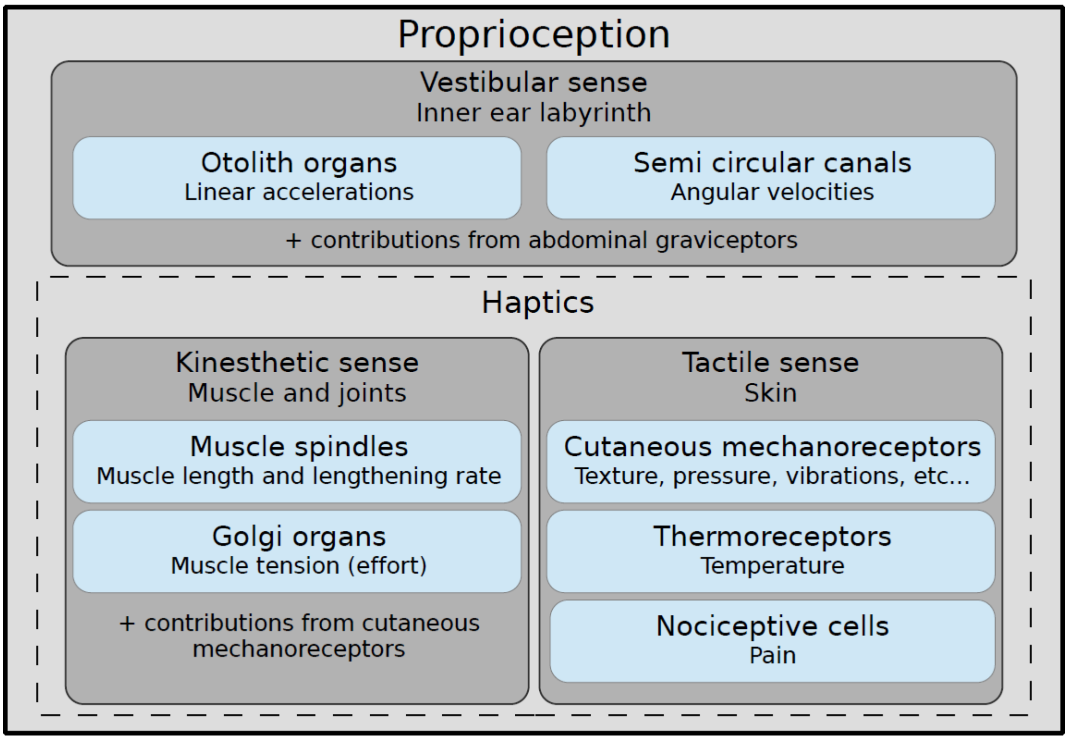


Fig. 1 : Proprioception terminology

2) The vestibular system

The vestibular system provide global motion informations : it is more or less our biological inertial unit. Its mechanoreceptors, the otolith organs and the semi-circular canals, are illustrated in Fig. 2. They are located in the labyrinth of the inner ear. The otolith organs detect linear accelerations of the head, whereas semi-circular canals react to angular velocities.

For a detailed description of the vestibular system, see [Lackner & DiZio, 2005].

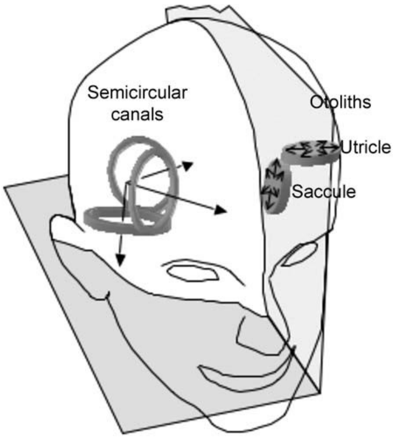


Fig. 2 : The vestibular mechanoreceptors
From [Lackner & DiZio, 2005]

However, “the vestibular system is involved in several aspects of human functioning besides the perception of acceleration, including the reflexive control of gaze stabilization (to maintain clear vision during head movement), head righting, postural equilibrium, coordinated locomotion, certain reaching behaviors, and even way finding” [Hale & Stanney, 2014]. One should also notice that receptors sensitive to gravity were also found in abdominal viscera [Mittelstaedt, 1995].

3) The kinesthetic system

The kinesthetic sense, also called kinesthesia, refers to the perception of the body configuration and limb movements. The mechanoreceptors mainly involved were found to be located in muscles (muscle spindles), tendons (Golgi organ) and joints.

Muscle spindles

Muscle spindles, illustrated in Fig. 3, detect changes in muscle length. They consist of intrafusal fibers attached in parallel with extrafusal muscle fibers. There can be found two types of sensory endings in muscle spindles: the primary and secondary endings, which are both triggered when the muscle stretches.

The primary sensory fibers (Type Ia), which are the largest and the fastest, respond to the rate of stretch, i.e. changes in muscle stretch velocity. As they only fire when muscle's length is changing, one say that they are rapidly adapting (RA), or phasic: when the muscle stops changing length, they do not fire anymore as they had adapted the the new length.

The secondary sensory fibers (Type II) produce a nervous signal representative of muscle's length. They are therefore considered as slowly adapting, or tonic : they keep producing action potentials when there is no change in muscle length. Their conduction speed is about two times slower than primary fibers.

Muscle spindles react only to muscle stretching, but thanks to the agonist-antagonist configuration of the muscles, whenever a muscle is contracted to move a limb, another one is stretched; hence stretch detection is sufficient to monitor limb movements in any direction.

However, the precise functioning of muscle spindles and their exact role in proprioception remains a delicate question which was debated for more than a decade in the 1960s and the 1970s [Paillard & Brouchon, 1968]. Their sensitivity, for instance, is modulated by the activity of gamma motoneurons, which leads to complex regulation mechanisms in practice.

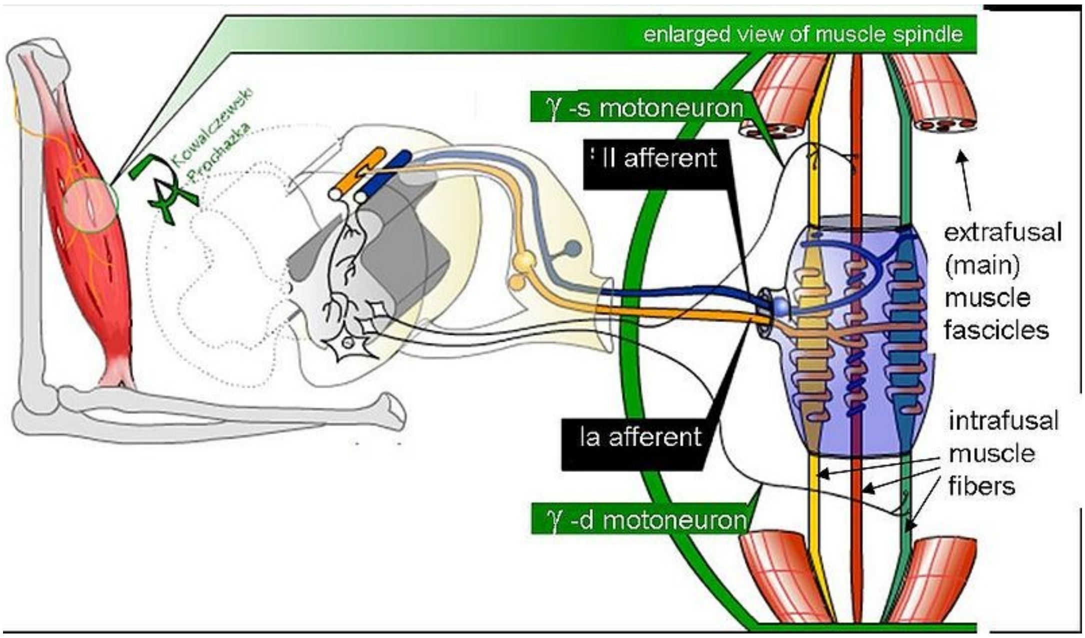


Fig 3 : Schematic view of a muscle spindle.
Intrafusal fibers are attached in parallel with extrafusal fibers.
Primary (Ia) and secondary (II) sensory nerve fibers spiral around the intrafusal muscle fibers and transmit their signal to the spinal cord.
Their activity is modulated by the gamma motoneurons.
From physio-pedia website

The stretch reflex

The stretch reflex (also called the myotatic reflex) contracts the muscle in case of unexpected lengthening. It is the famous knee-jerk reflex tested by doctors by taping the tendon under the knee, causing the leg to kick. This reflex regulates muscle length and is thus crucial for motor control. It also protects the muscles for excessive tension : while the muscle is reflexively contracted, the antagonist is also relaxed (its alpha motoneurons being inhibited).

The stretch reflex is triggered by the muscle spindles activity in the absence of motor command. Consequently, when the muscle spindles are artificially stimulated by vibration (as we will see later) the stretch reflex is activated and muscle contracts automatically.

The Golgi organ

The Golgi organs (innervated by Ib afferent fibers) are located in the tendons, near the junction with the muscle. Unlike muscle spindles, they are attached in series and are thus sensitive to the tension in the tendon, therefore in the muscle. Their activity is representative for the effort of the muscle.

The Golgi tendon reflex

The Golgi tendon reflex (also called the inverse myotatic reflex) protects muscles from excessive tension by relaxing it automatically and contracting antagonist muscle.

4) The tactile sense

Cutaneous contact produce very diverse and rich sensations, thanks to a variety of mechanoreceptors distributed all over the body. Besides the temperature and the pain perception, which have their own receptors and can be relatively easy characterized, the touch perception is certainly the sensory system the most complex to apprehend and to describe.

Its manifold mechanoreceptors, represented in Fig. 4, are distributed all over the body, but not equally (glabrous skin, like palm of the hand, is much more sensitive than hairy skin, like arms or back), which brings a first conceptual difficulty for any experimental approach : which part of the body should be stimulated and why ?

Although there is still a lot of grey areas about their functioning, four types of skin mechanoreceptors were identified in the glabrous skin, each of them exhibiting distinct properties : the Merkel discs, the Meissner corpuscles, Ruffini endings and Pacinian corpuscles. For more information on this, see [Pasquero, 2006].

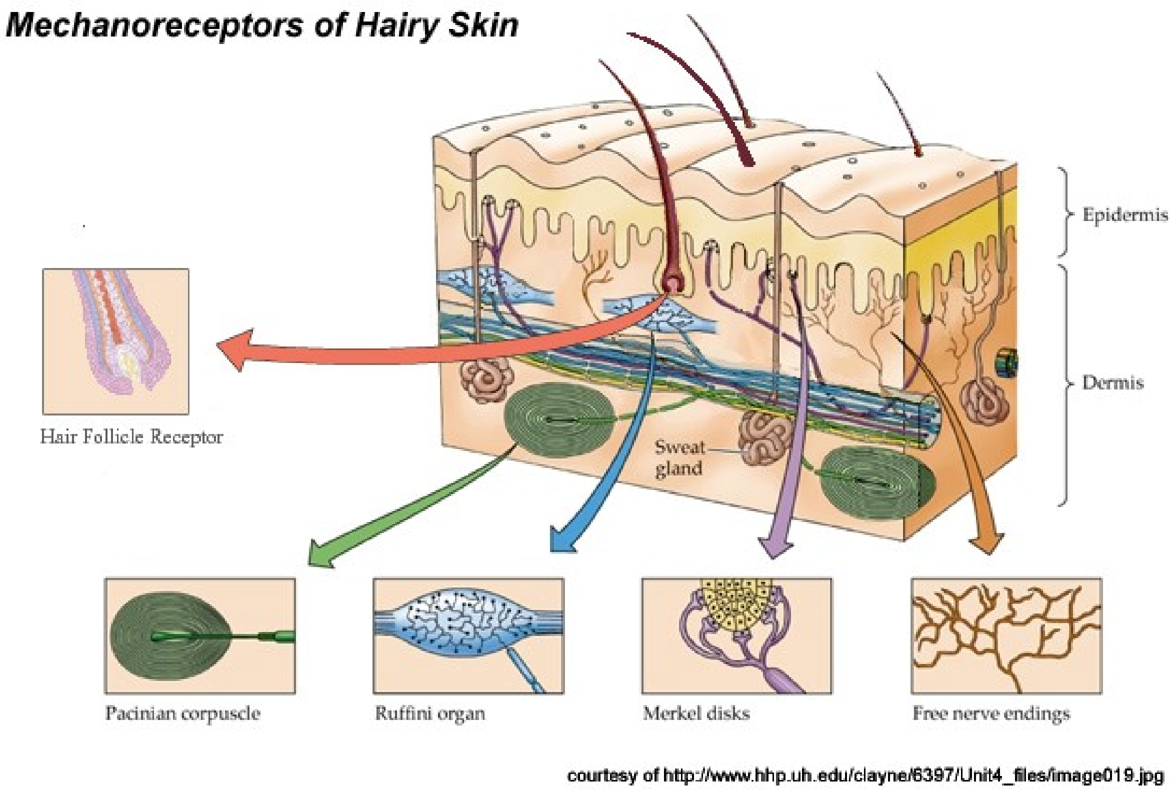


Fig 4 : Mechanoreceptors of hairy skin

Another difficult question is the one of the standard stimuli (or feature to identify) to choose among the numerous possible ones. For instance, to identify a texture, many parameters will be taken in account like microscopical shape, pressure distribution, sliding resistance, but also temperature, humidity, or even sound. Also, active or passive explorations can result in similar detection performances for certain features like weight, or slightly different detection performances for other features like shape.

If the skin mechanoreceptors are the main involved in tactile perceptions, other sensory systems (like kinesthesia, thermoception or audition) may be involved, depending on the detected feature and the context. In fact, this seems to be true for every sensory system.

5) Sensory integration

Even if the previous introduction may give a picture of clear distribution of the perception abilities among several distinct sensory systems, each of them detecting informations of different nature, one should be careful with this “functionalist” view.

Whereas it is often reasonable to consider exteroceptive senses like sight and audition as isolated systems, numerous experiments show that informations from different sensory systems may contribute to proprioceptive perceptions. To give just a few examples, heat plays a role in weight evaluation [Stevens, 1979], texture characterization may be affected by sound [Jousmäki & Hari, 1998], and feet vibration may elicit a sensation of whole body acceleration when combined to suggestive yet immobile visual context [Nordahl et al., 2012].

It is likely that all “available data” are perpetually combined in a subtle and complex processing distributed through the nervous system, to produce conscious perceptions as well unconscious mechanisms like muscle coordination.

Despites, this powerful interpretation ability may be misled when certain perceptual limits are crossed : we experience then an illusion.

II. Kinesthetic illusions – state of the art

1) Introduction

Kinesthetic illusions appear in the literature in the 70s (for a review, see [Jones, 1988]). The first authors using this term were studying and discussing the role of muscle mechanoreceptors in the perception of the body and its movement [Goodwin et al., 1972]. These mechanoreceptors, called muscle spindles, react to muscle activity and are essential for muscle length regulation, and therefore for global motor control. Discovered in the 60s [Hagbarth & Eklund, 1966], their exact role in human motion mechanisms were intensely discussed for two decades [Jones, 1988].

Muscle vibration was used in experiments in the early 70s [Eklund, 1971] [Goodwin et al., 1972] to stimulate them artificially, and appeared to produce illusory limb movement sensations when the reflexive movement produced by the vibration is hindered. Later in the 90s and the 2000s, particular effects of leg and neck muscle vibration were studied [Wierzbicka et al., 1998] [Ceyte et al.,2006] [Ceyte et al.,2007]. As we will see in the following part, the stimulation of these muscles causes global body tilt responses, therefore a possibility for a global movement illusion.

One should mention the Laboratory of Human Neurobiology from the Université de Provence/CNRS, which published dozens of papers over almost three decades about muscle spindles functioning and vibration-induced kinesthetic illusions [Roll & Vedel, 1982] [Gilhodes et al., 1986] [Roll et al. 1989] [Wierzbicka et al., 1998] [Calvin-Figuière et al., 1999] [Calvin-Figuière et al., 2000][Albert et al., 2006][Roll et al. 2009][Thyrion & Roll, 2010].

Several other kinesthetic illusion techniques, discussed in a second part, appeared only recently and were marginally experimented, so that muscle vibration remains the main one.

2) Muscle vibration

(a) Principle

When a muscle is vibrated between 60 and 120 Hz with an amplitude from 0.1mm to 1mm, muscle spindles primary endings are stimulated [Roll et al. 1989] and the stretch reflex is triggered, which means the vibrated muscle contracts automatically. This is called the Tonic Vibration Reflex (TVR).

If the induced movement is stuck and if there is no visual cue about the limb's movement, an illusory movement in the opposite direction may be perceived by the subject. The term of “kinesthetic illusion” refers to this phenomenon.

[Goodwin et al., 1972] is the historical experiment demonstrating this. The perceived motion was evaluated by asking the blindfolded subjects to mimic it with the other arm. The vibrated arm was fixed to a splint which could rotate at the elbow. The splint was also attached to a string blocking its rotation after around 140°. As shown in Fig. 5, the kinesthetic illusion onset coincides with the impediment of the vibrated arm.

Subject's age does not seem to play a role in these effets [Quoniam et al., 1995].

Illusion's intensity seems to be function of the vibration frequency, at least between 40 and 80Hz [Cordo et al., 2005].

The illusion does not arise only from the vibrated muscle's proprioceptive signals, but rather from the asymmetry with those from the antagonist muscle : if both are vibrated, the perceived velocity of the illusory movement is related to the difference between the vibration frequencies, the illusion being absent with equal frequencies [Gilhodes et al., 1986].

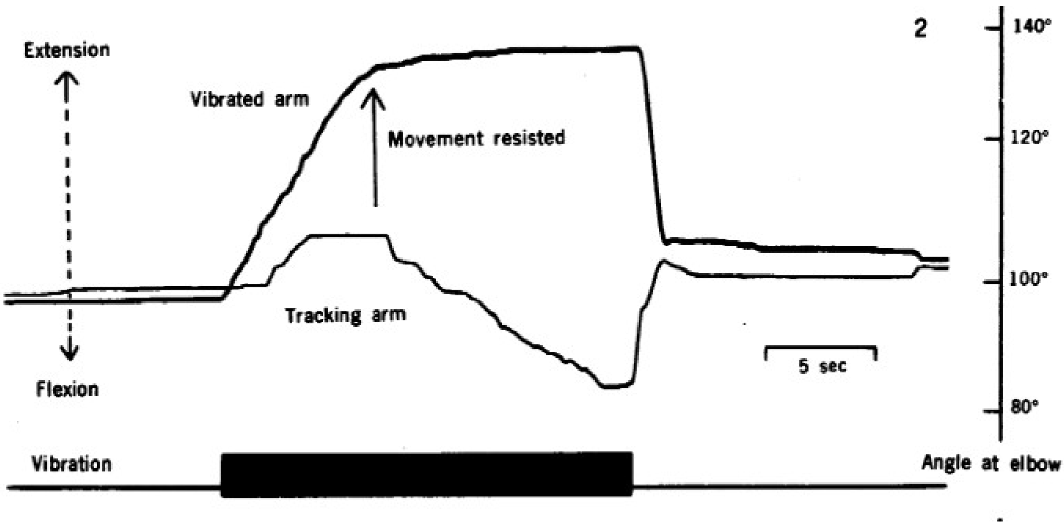


Fig 5 : Arm rotations over time during triceps vibration.
The tracking arm's displacement indicates that the blindfolded subject experienced an illusory flexion from the moment the vibrated arm is stuck.
From [Goodwin et al., 1972]

[Naito et al., 1999] studied the precise effects of the vibration frequency in the kinesthetic illusions features. It appears clearly that effects are maximised around 70-80 Hz (Fig. 6). “Vividness was defined as the clarity of the experience compared with an actual arm movement. When they felt the illusory arm movement as if their arm were actually moving, they should have scored 10. The continuance was their subjective scaling on how long they felt the illusion during the 60 sec. If they felt the illusion throughout the whole period of stimulation, they should have scored 10. The strength of illusion was how much the arm moved. If they felt that the arm had been maximally extended, they should have scored 10. When they did not feel any illusion at all, they should have scored 0 in all three questionnaires.”

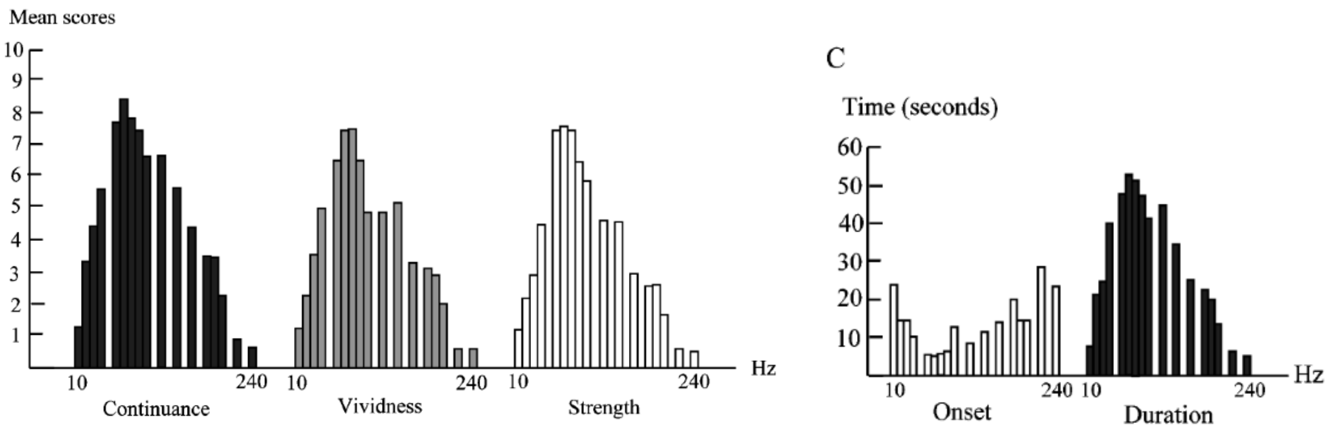


Fig 6 : Kinesthesic illusions features according to frequency
From [Naito et al., 1999]

Interesting experiments were conducted by [Lackner et al., 1984] to study the influence of vision on these vibration-induced kinesthetic illusions (see Fig 7).

(b) Body deformation illusions

Some experiments of body deformations illusions induced by muscle vibration are also mentioned, the most famous being the Pinocchio illusion : if one holds with eyes closed its nose during biceps vibration, the nose seems to elongate (see Fig 7. B). Another example is the illusion of a shrinking waist when hands are on the hips while triceps are vibrated [Dizio et al., 2014].

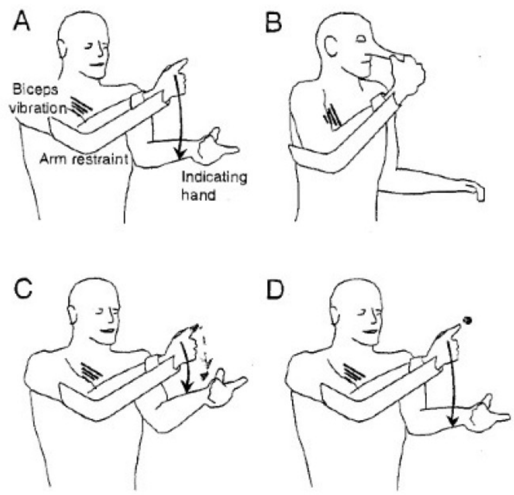


Fig 7 : Influence of vision on kinesthetic illusions induced by biceps vibration in darkness.
A. In complete darkness, biceps vibration elicits illusory extension of the restrained forearm, measured by the position of the unrestrained arm with which the subject indicates the felt position.
B. Pinocchio illusions : in complete darkness, elongation of the nose is experienced when it is grasped by the hand of the arm undergoing illusory elbow extension du to biceps vibration.
C. When just the index finger of the vibrated arm is made visible with phosphorescent paint in an otherwise dark room, the participant sees the stationary finger move down and feels the forearm displace less than in complete darkness.
D. A dim target light located 1mm away from the fingertip of the restrained vibrted arm looks stationary while the concurrent apparent downward displacement of the arm is as great as in complete darkness during biceps vibration.
From [Dizio et al., 2014]

Despite the interest of these original findings, one should notice that they have been very much mentioned but apparently never reproduced.

(c) Postural effects of muscle vibration

About two decades later (mainly in the 1990s and the 2000s), the postural effects of leg and neck muscle vibration were studied in many papers. As this muscles elicit a global body tilt when contracted, attempts were made to produce global illusory movements.

"A stimulation of the same muscle may produce various illusory movements dependent on the postural, cognitive, and multisensory context. For example, switching from segmental to postural sensation is possible if the stimulated wrist muscle becomes functionally involved in the whole body posture such as in a case of leaning on the hand against the wall." [Wierzbicka et al., 1998]

Vibrating the Achilles tendon stimulates the Gastrocnemius and the Soleus muscles. These muscles are involved in postural control to oppose gravity, as well as the Tibialis Anterior which acts in the opposite direction [Gomez et al., 2009]. The vibration induces a backward body tilt, and if the standing position is restrained, an illusory forward tilt is experienced [Lackner & Levine, 1979].

[Ceyte et al.,2007] had an interesting set-up showed in Fig 8 : subjects were attached to a rotating backboard and could adjust their vertical orientation with a joystick. Starting from randomized positions, they tended to adjust their body backward when their Achilles tendon was vibrated compared to the condition with no vibration.

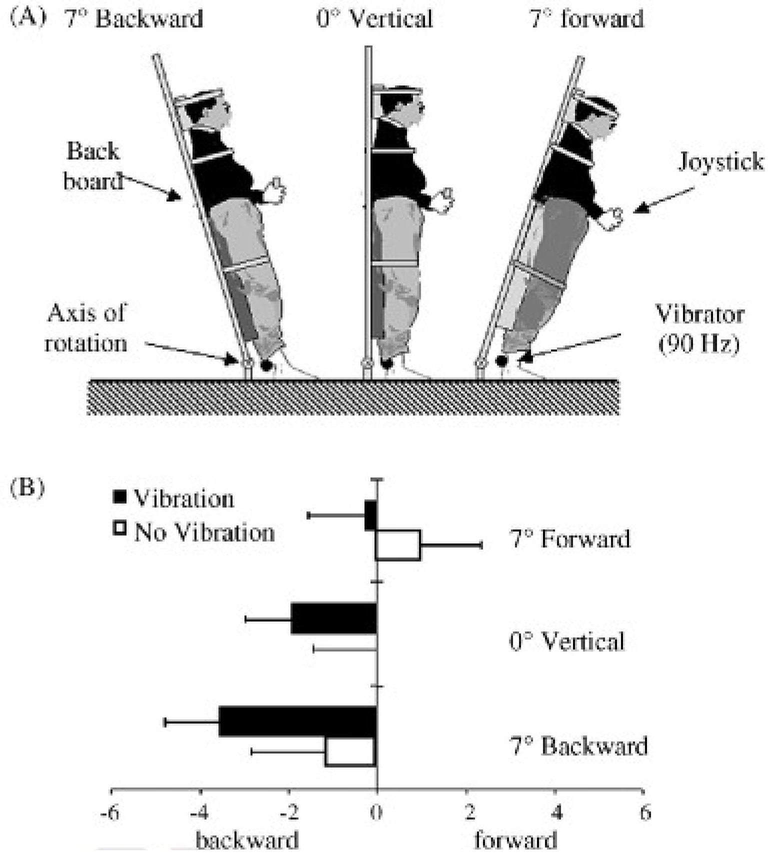


Fig 8 : Set-up and results from [Ceyte et al.,2007]
(A) The subjects were strapped on a backboard that could be rotated in the antero-posterior direction with the axis of rotation at the level of the ankles
(B) Mean settings errors (°) as a function of initial body orientation with or without vibration. Error bars indicate the standard deviations.

Neck muscles like Trapezius, Splenius and Sterno-cleido-mastoidus may also be vibrated to alter spatial orentation perception. However the effects are generally weaker [Wierzbicka et al., 1998].

"Previous research showed that neck muscle vibration does not induce kinaesthetic illusions in all subjects, perhaps due to differences in individual sensitivity for transcutaneous vibratory stimulation of neck muscle spindles (see Lackner and Levine 1979 ; Biguer et al. 1988)." [Karnath et al., 2002] Most authors indicate also the difficulty to stimulate one specific muscle in this region [Strupp et al., 1998] [Ceyte et al.,2006], which may be the main reason of these low results.

[Lackner & Levine, 1979] is one of the first publication to support the idea of global kinesthetic illusions. It seems also to be the most cited on the topic. [Lackner & DiZio, 2005] claimed that “in fact, with vibration of the appropriate skeletal muscles, apparent motion and displacement of the body or its segments can be elicited in virtually any desired configuration.”

However, one should notice that the experimental results of neck or leg muscles vibration are pretty different than those of arm or wrist simulation, although the term of kinesthetic illusion is indifferently used in both cases. The first ones are static, whereas the second ones are dynamic. Whereas a stuck vibrated arm gives a *constant velocity movement illusion* [Goodwin et al., 1972], neck and leg stimulation produce a *body tilt of constant angle* [Strupp et al., 1998][Wierzbicka et al., 1998][Karnath et al., 2002] [Ceyte et al.,2006][Ceyte et al.,2007]. As discussed in [Adamcova & Hlavacka, 2007], the effect of Achilles tendon vibration is a perturbation of verticality perception, which is in fact very different than a continuous tilt feeling.

(d) Movement generation

An ambitious extent of the muscle vibration technique consist to stimulate several muscles of a limb to induce elaborated 2D or 3D kinesthetic illusions evoking precise movements. A very intersting approach was first proposed by [Albert et al., 2006], later continued by [Roll et al., 2009] and [Thyrion & Roll, 2010].

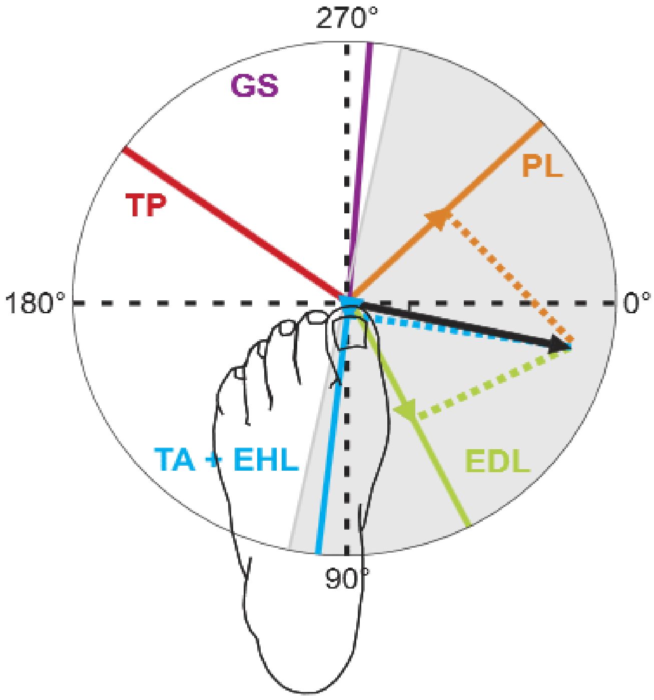


Fig 9 : Proprioceptive model of leg muscles.
The instantaneous velocity vector is orthogonally projected onto the previously determined preferred sensory direction of each muscle :
tibialis anterior [TA], extensor hallucis longus [EHL], extensor digitorum longus [EDL], peroneus lateralis [PL], gastrocnemius soleus [GL] and tibialis posterior [TP].
Only the preferred sensory directions within a 180° area around the instantaneous movement direction (in grey) are taken in account in the projection.
From [Roll et al., 2009]

Based on many years of experimental microneurography, they established a very simple but effective model of muscular nervous activity regarding the contribution of the muscle to the movement, called the “population vector model” (Fig.9). As each muscle can move a limb in only one direction, its contribution to the limb's movement can be modelised as a vector, the amplitude of which corresponds to its muscle spindles' activity. Any movement can thus be decomposed in the set of the contributions of each muscle over time, and applied to any limb.

These authors managed to induce recognizable illusory movements in the ankle or in the hand (Fig. 10). However one should keep in mind that these results were obtained in controlled experimental conditions and that the subjects were selected for their sensitivity to kinesthetic illusions.

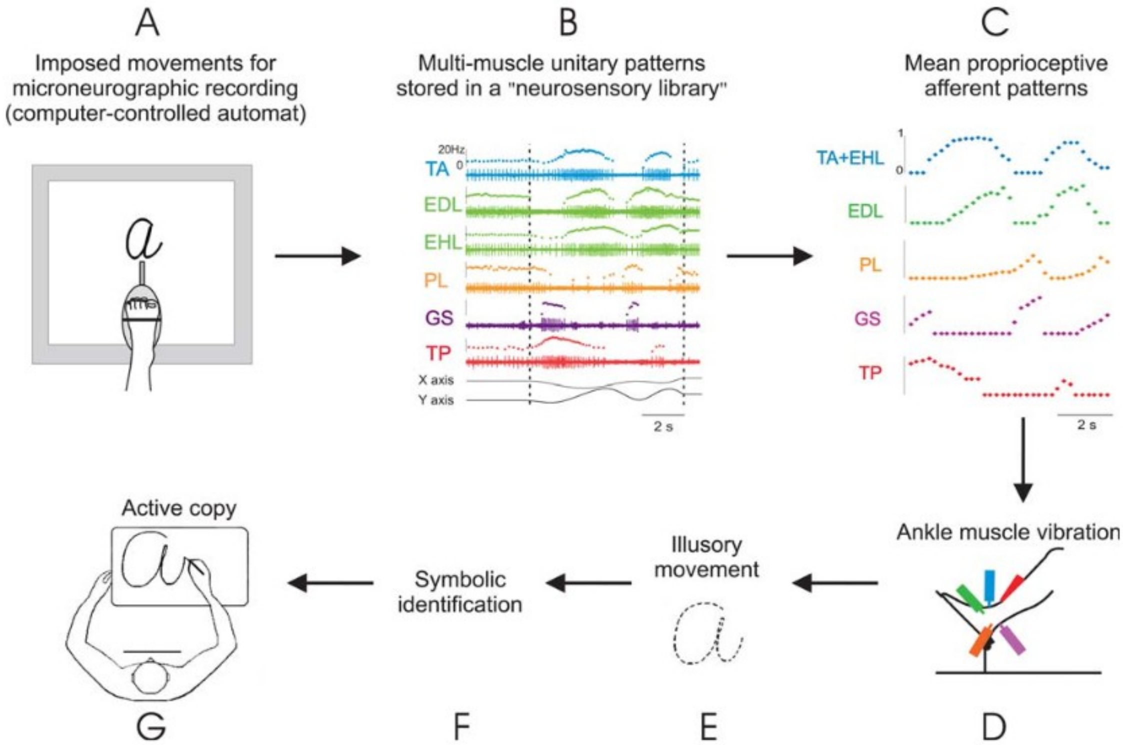


Fig 10 : Proprioceptive patterns are experimentally measured then used to pilot muscle vibration.
Subjects draw the perceived trajectory on a digitizing tablet.
From [Roll et al., 2009]

3) Other kinesthetic illusion techniques

(a) Galvanic vestibular stimulation

Applying a small continuous current between the mastoids (Fig. 11) is another way to disturb vestibular signals and eventually produce illusory movements. “On a standing subject, a low-intensity current passing across the two mastoid processes induces a lateral tilt towards the anode side. At current cut-off tilt in the opposite direction is observed.” [Tardy-Gervet & Severac-Cauqui, 1998] To get predictible results, the stimulation should be regulated in current [Johannson et al., 1995].

“When GVS caused freely standing subjects to sway, they accurately perceived the direction of that movement. These were described for stimuli of 400 ms duration or greater, but not for 40 ms stimuli. In contrast, when subjects were immobilized GVS only evoked illusory movements for stimuli of 1 s or longer, and even at 1 s they were uncommon. Thus the illusory and the sway responses have time courses that prevent them being causally related. Furthermore, the sway response is affected by the subjects' posture, whereas the illusion is not." [Wardmann et al., 2003]

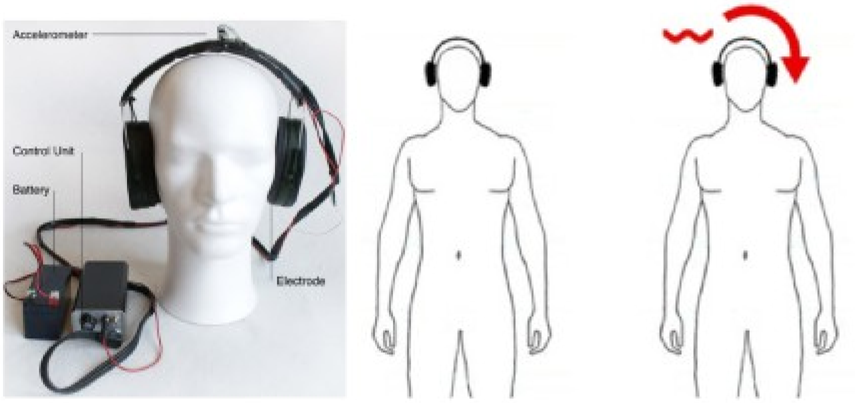


Fig 11 : Galvanic vestibular stimulation principle.
From [Ruhl & Lamers, 2011]

This technique was mainly studied during the 1999s and the 2000s, but the experimental conclusions are still incomplete or contradictory : "It is uncertain how the central nervous system interprets and responds to this altered vestibular signal to produce the motor response. The response is complex, depends on task, posture and the availability of other sensory information. The size of the response increases when subjects stand with their feet close together, stand on an unstable support surface, or when proprioceptive, visual or tactile sources of sensory information are limited." [Wardmann et al., 2003]

(b) Tendon electrical stimulation

One author [Kajimoto, 2005] proposed to stimulate the tendon electrically. A current controlled rectangular pulse of 10 mA and voltage from 0 to 150V was applied to arm tendons (see Fig. 12) to induce an illusory force (instead of an illusory movement). In some subjects the stimulated arm moved involuntarily (maybe because of the Gogli tendon reflex ?). Subjects reported illusory force and/or illusory movement sensations.

Despite the paper is remarkable, the study is not statistically significant and conclusions cannot be made from experimental results. It seems to be the only publication on this topic however.

Fig 12 : Electrodes placement.
From [Kajimoto, 2005]

(c) Hanger reflex

This technique is for sure the most unexpected and incongruous way to produce a kinesthetic illusion : placing a wire hanger on the head with a light offset, so that the pressure is applied above one of the eyebrows, generates an illusory force rotating the head gently (Fig. 13).

This phenomenon has still no scientific explanation, and it was popularized in Japan as such in a TV show. The Electro-Communications University of Tokyo has published several papers on the topic [Matsue et al., 2008][Sato et al., 2009][Nakamura et al., 2014][Nakamura, 2014], but with questionable methods and alsmost no consistent results.

Fig 13 : The Hanger reflex.
From [Matsue et al., 2008]

We experimented this simple (and fun) testing on a dozen of voluntary subjects : it was found to be relatively reproducible (about 70-80% of partipants experiencing the illusory force), although the method is hazardous (as the cause of the illusion is no known). The effect is quite weak and it is easy to resist to the illusory force.

[Nakamura et al., 2014] used medical plastic casts instead of a hanger (Fig. 14) and noticed that the phenomenon could be reproduced at wrist and waist. However, there is no substantial explanation about the reflex mechanism itself : it is still undetermined, for instance, if the triggering stimulus is the local pressure distribution, the torque generated on the limb or something else.

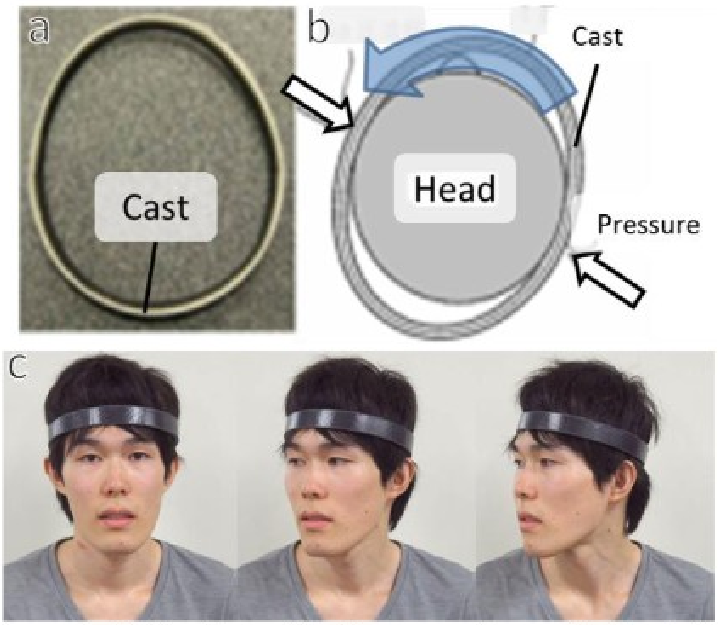


Fig 14 : Use of plastic casts instead of a wire.
From [Nakamura et al., 2014]

(d) Feet stimulation

Vibrations applied to the foot sole can reach leg muscles and elicit similar effects than ankle stimulation [Kavounoudias et al., 1999].

A vibrotactile approach, vibrating the sole skin instead of tendons (see Fig. 16), was proposed recently. Combined with a visual context, it was found to modulate [Farkhatdinov et al., 2013] or even induce vection [Nilsson et al., 2012].

[Nordahl et al., 2012] went a bit further and got interesting results. A very basic and rough vibratory signal (50Hz square-wave) were applied to the foot sole via custom shoes while subjects were placed in different contexts (Fig. 15) with the help of a virtual reality headset. Some visual scenes were suggestive (an elevator, a train) but there were no explicit clues of movement (train's windows were shut for instance). The other conditions were darkness, and a bathroom, chosen because such an environment is unlikely to be assiociated with movement. Despite the very poor physical significance of the stimulus, subjects reported vection in most cases; most interestingly, the reported direction was highly related to the visual context : up or down in the elevator, forward or backward in the train, and apparently random directions for the bathroom and the darkness conditions.

Fig 15 : Screenshots of three of visual contexts :the train, the elevator, and the bathroom
From [Nordahl et al., 2012]

Fig 16 : Placement of a pressure sensor and two actuators in the heel of one sandal.
The pressure sensors was used to ensure that vibration only was activated when the foot is in contact with the ground.
From [Nordahl et al., 2012]

4) Discussion

Muscle vibration is, by far, the most well-known technique to elicit kinesthetic illusions. However, despite dozens of publications over more than a half-century, there is still a lot of grey areas about its limits and possibilities. For instance, the question of reproducibility is very rarely addressed and most authors even select subjects on their sensitivity. This may be partly explained by the diversity of the authors' approaches, and partly to the difficulty to standardize the stimulus (for instance, fixing the vibrator with a given pressure no matter the subject's morphology). Moreover, the combination with other modalities like vision has almost not at all been explored.

The four other techniques presented in **3)**, on the contrary, were only explored by nothing more than several publications each. From the mainstream technology product's point of view, electrical stimulation address the questions of safety and consumer acceptance. Tendons could probably be electrically stimulated in a safe way to elicit various illusions, but the lack of knowledge on this topic should be first filled. The hanger reflex will remain a simple curiosity until one find a way to identify its precise stimulus, which is already a challenge. The feet stimulation is a promising approach to induce motion sensations. In addition to the possibility of affecting body posture via tendon vibration, the recent vibrotactile approach gave convincing results even with a very basic stimulus.

Among these possibilities, one approach had to be chosen for the experimental part of the internship. We decided to first examine the reproducibility of the muscle vibration technique, and secondly the effects of combining it with a visual stimulus. Setting up the experiment also means choosing an appropriate actuator, which is actually an epineous question. As there is no shop selling vibrators for kinesthetic illusions, a state of the art had to be established about the different existig technological solutions, which have very distinct pros and cons.

III. Vibrators – state of the art

1) Eccentric Rotating Mass (ERM)

(a) Presentation

With the development of vibrating devices (pagers and gamepads at first, smartphones nowadays, but also medical instruments or industrial tools), miniaturized ERM have been designed and produced in vast quantities. There is now a wide offer for cheap, small and robust designs of this very simple device : a DC motor with a non-symmetric mass attached to the shaft. It used to be also called « pager motor », « rumble motor », or simply « vibration motor ».

ERM can be of various shape (cylindrical or coin, aka « pancake », see Fig. 17 and 18), with exposed or encapsulated mass. The typical diameter is of 1cm, and the typical consumption is of 50 to 100 mA.

Fig. 17 : ERM of various shapes
Left : cylindrical pager motor with exposed mass
Center : PS3 gamepad rumble motor
Right : typical smartphone « pancake ERM »
From [Yao & Hayward, 2010]

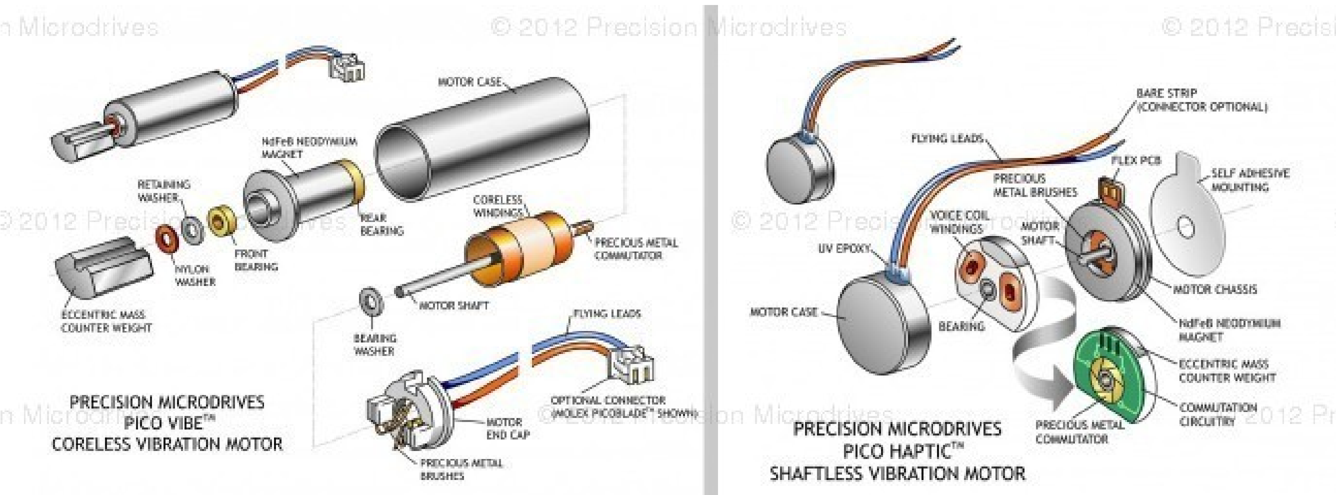


Fig 18 : Exploded view of a cylindrical shaped ERM and a « pancake » ERM
From Precision Microdrives website

(b) Typical features and specifications

Price	Diameter	Rated current	Acceleration	Latency	Control
1-5$	10mm	50-100mA	2g@3.6V	40-80ms	DC

(c) Driving methods

As the motor is a classical DC motor, the speed rotation is proportional to the voltage applied at terminals. As the angular acceleration is proportional to the squared angular velocity, the acceleration amplitude of the vibration grows quadratically with its frequency (Fig. 18).

This coupling is the main limitation of ERM : they can't vibrate at different amplitudes for a single frequency, and they can't vibrate at the same amplitude for different frequencies.

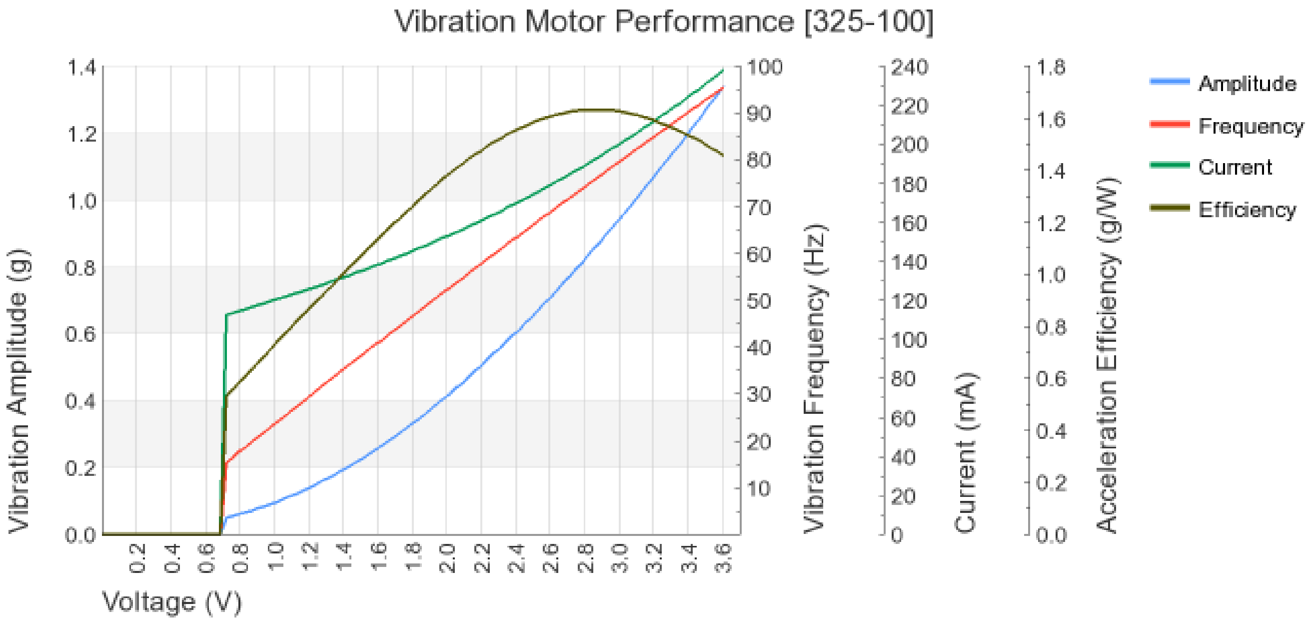


Fig 19 : Typical ERM performance curves :
amplitude grows quadratically with frequency
From Precision Microdrives website

As the movement is rotative, the acceleration is transmitted in two dimensions. For some applications, this can result in unwanted effects, or a poor efficiency in energy transmission.

« A simple off-on voltage signal applied to the motor at rest from a low-impedance voltage source drives the angular velocity in a first-order step response with a time constant equal to the spinning parts' moment of inertia, divided by a damping coefficient resulting from friction and the motor's back electromotive force (back-EMF). » [Hayward & Maclean, 2007]

The ramp-up period of this first-order is typically of tens to one hundred milliseconds, which can be another limitation for subtle haptic uses. Fig. 20 shows this unwanted transitory phase in the force response of an ERM to a step input.

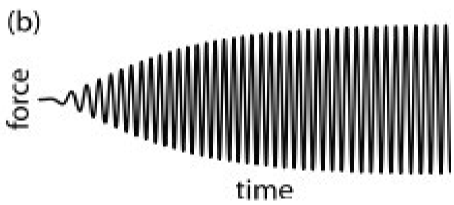


Fig 20 : Chirp-like response of an ERM to a step input.
From [Yao & Hayward, 2010]

However, some power handling techniques allow to change this dynamic behavior. Overdriving the voltage during transient regime, or « active braking » decrease rise and stop time.

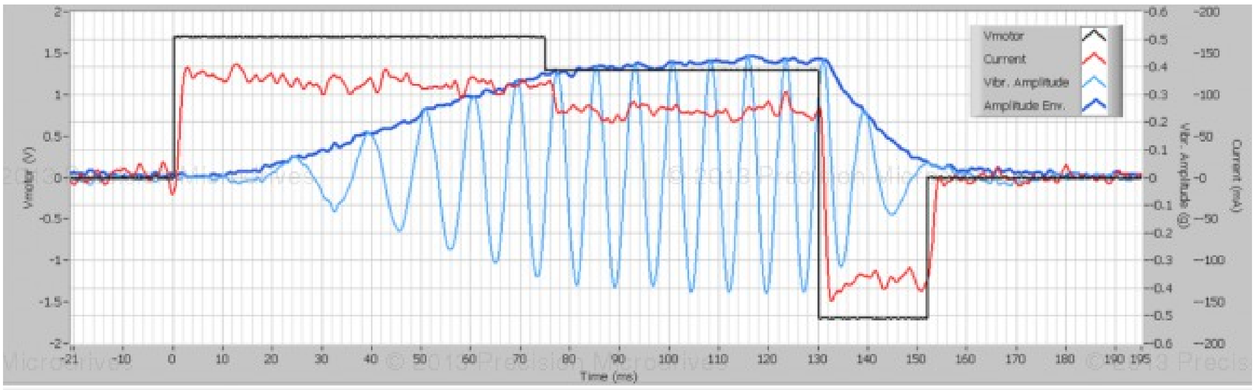


Fig 21 : Typical ERM overdrive step response test
From Precision Microdrives website

Some authors suggest trickier approaches, like simply switching from a voltage source to a current source to get a quick rise and short-circuit the motor to get an effective brake [Hayward & Maclean, 2007]. Switching power at high rates may also allow a « tap » effect, or even more complex behaviors.

(d) Other techniques

To bypass the frequency-amplitude coupling problem, some authors suggest to combine several ERM in one « vibel » (see Fig. 22). If ERM are have similar features, a N-motor « vibel » offers N different levels of amplitude for a given frequency, depending on how many motors are activated. [Cipriani et al., 2012]

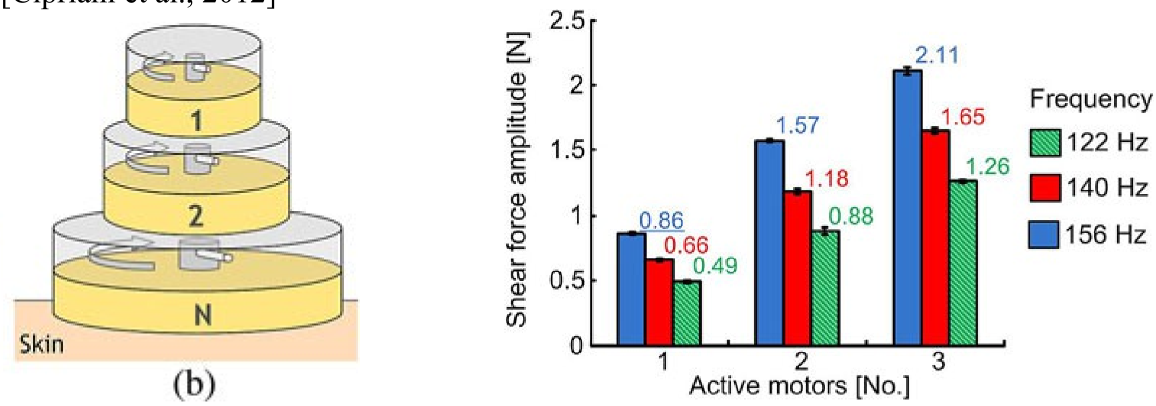


Fig. 22 : a 3-ERM « vibel »
Left : a 3-ERM « vibel »
Right : For each frequency, the « vibel »
can produce three different vibration amplitudes
From [Cipriani et al., 2012]

Another lead would be, of course, an ERM with the ability of moving its mass in relation to its axis, modulating therefore the vibration frequency for a given kinetic energy.

2) Linear Resonant Actuator (LRA)

(a) Inductive transducers

An alternative way of producing vibrations is applying an alternative current to a coil wound around a magnetic or metallic core, resulting in a linear back and forth movement. Contrary to ERM, this vibration is unidimensional (*along* the axis) instead of bidimensional (*around* the axis), thus much more precise and located (see Fig. 23). These actuators (forming what we may call the inductive transducers family) are in fact quite diverse.

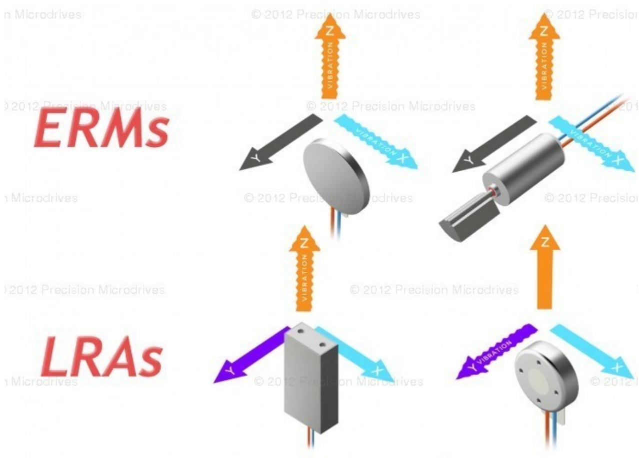


Fig 23 : 2D vibration against 1D vibration
From Precision Microdrives website

Loudspeakers have a fixed magnetic core and a moving coil linked to a membrane (to transmit vibrations to the air). The coil is generally designed as light as possible to minimize inertial effects, which would alter frequency response, and thus signal fidelity. Therefore, the forces involved are rather weak compared to other inductive transducers.

Solenoids can be seen, from a signal treatment view, as the opposite of loudspeakers. They have a fixed coil and a iron core (sometimes attached to a spring). Their core has a strong inertia and a very bad dynamic behavior, as their purpose is to push strongly at low rate and not to vibrate.

Haptics actuators (sometimes called tactors) should ideally achieve both high power and high frequency accuracy; this is why loudspeakers and solenoids are often a poor choice.

Voice-coil actuators (also called voice coil linear motors) consist of a moving magnet sliding within a fixed coil. Its sharp and balanced shape allow a localized, precise action with a quite flat frequency response. Therefore, voice-coil actuators are generally suitable for vibrotactile applications. Nevertheless, to get amplitudes able to reach deeper body parts like tendons or muscles, they need to be much bigger than ERM and could hardly be used in an embedded device (see Fig. 24 for an example).

Although such skin actuators were first developed by Gault in the 1920s (!) [Gault, 1924], the industrialization of such devices is quite recent, and still immature. As a comparison, Precision Microdrive's catalog offers 60+ models of ERM for only 3 voice-coil actuators models.

If the magnet of a voice-coil actuator is let free, only the force applied can be controlled in closed-loop. In order to control the position (and eventually, the vibrations), one have to add some mechanical part to this device.

Fig 24 : Voice-coil actuator used for a kinesthetic illusion experiment
From [Leonardis et al., 2012]

(b) Presentation

A LRA is a voice-coil actuator with a spring linking the coil and the magnet. Its dynamic behavior is therefore of a simple spring-mass system (Fig. 25), with a single resonance frequency. This means a LRA can only vibrate at this frequency which is its main limitation. On the other hand, it offers a very good amplitude control with a latency under 30 ms, which allows a variety of advanced signals like single or double tap, increasing or decreasing ramp, etc.

LRA have been developed recently to meet the demand for handheld devices (shop scanners, torque wrenches…) able to generate several distinct haptic signals. They are often as small as a « pancake » ERM, but also weaker. Their resonance frequency are between 150 et 250 Hz. Nonetheless, one should expect new designs and features to occur over the coming years.

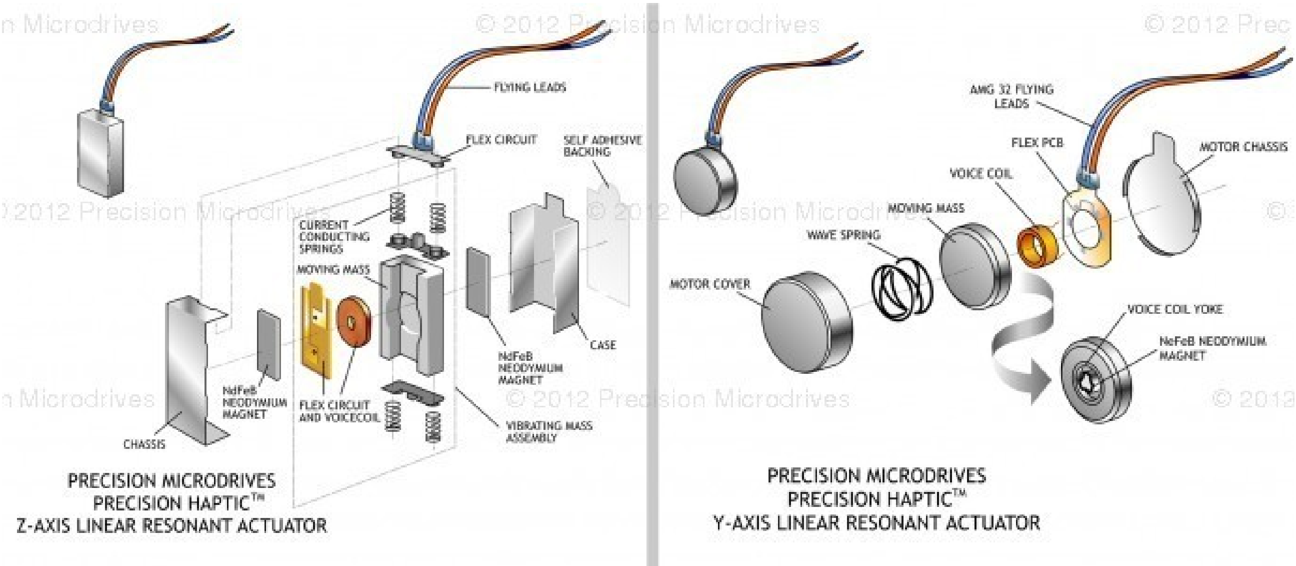


Fig 25 : Exploded view of two LRA designs
From Precision Microdrives website

(c) Typical features and specifications

Price	Diameter	Rated current	Acceleration	Latency	Control
5-10$	10mm	50-100mA	1g@1.5V	20-30ms	AC

(d) Driving methods

Except for the resonance frequency, LRA are similar to loudspeakers : the simplest way to get it to vibrate is to plug it to an audio source. The use of electroacoustic tools (like a sound synthesis software and an audio amplifier) is a simple, quick and explicit way to drive them.

Another approach is to use a specific driver creating so-called « haptic waveforms », i.e. command patterns designed to produce precise vibrotactile signals : click, tap, bump, ramp, buzz... The most popular driver at the moment is the DRV2605, which comes with 100+ haptics waveforms included (Fig. 26). However, apart the amplitude variation, quick and basic tests revealed than less than 10 effects were clearly distinguishable from each other.

11.2 Waveform Library Effects List

EFFECT ID NO.	WAVEFORM NAME	EFFECT ID NO>	WAVEFORM NAME	EFFECT ID NO.	WAVEFORM NAME
1	Strong Click - 100%	42	Long Double Sharp Click Medium 2 – 80%	83	Transition Ramp Up Long Smooth 2 – 0 to 100%
2	Strong Click - 60%	43	Long Double Sharp Click Medium 3 – 60%	84	Transition Ramp Up Medium Smooth 1 – 0 to 100%
3	Strong Click - 30%	44	Long Double Sharp Tick 1 – 100%	85	Transition Ramp Up Medium Smooth 2 – 0 to 100%
4	Sharp Click - 100%	45	Long Double Sharp Tick 2 – 80%	86	Transition Ramp Up Short Smooth 1 – 0 to 100%
5	Sharp Click - 60%	46	Long Double Sharp Tick 3 – 60%	87	Transition Ramp Up Short Smooth 2 – 0 to 100%
6	Sharp Click - 30%	47	Buzz 1 – 100%	88	Transition Ramp Up Long Sharp 1 – 0 to 100%
7	Soft Bump - 100%	48	Buzz 2 – 80%	89	Transition Ramp Up Long Sharp 2 – 0 to 100%
8	Soft Bump - 60%	49	Buzz 3 – 60%	90	Transition Ramp Up Medium Sharp 1 – 0 to 100%
9	Soft Bump - 30%	50	Buzz 4 – 40%	91	Transition Ramp Up Medium Sharp 2 – 0 to 100%
10	Double Click - 100%	51	Buzz 5 – 20%	92	Transition Ramp Up Short Sharp 1 – 0 to 100%
11	Double Click - 60%	52	Pulsing Strong 1 – 100%	93	Transition Ramp Up Short Sharp 2 – 0 to 100%
12	Triple Click - 100%	53	Pulsing Strong 2 – 60%	94	Transition Ramp Down Long Smooth 1 – 50 to 0%
13	Soft Fuzz - 60%	54	Pulsing Medium 1 – 100%	95	Transition Ramp Down Long Smooth 2 – 50 to 0%
14	Strong Buzz - 100%	55	Pulsing Medium 2 – 60%	96	Transition Ramp Down Medium Smooth 1 – 50 to 0%
15	750 ms Alert 100%	56	Pulsing Sharp 1 – 100%	97	Transition Ramp Down Medium Smooth 2 – 50 to 0%
16	1000 ms Alert 100%	57	Pulsing Sharp 2 – 60%	98	Transition Ramp Down Short Smooth 1 – 50 to 0%
17	Strong Click 1 - 100%	58	Transition Click 1 – 100%	99	Transition Ramp Down Short Smooth 2 – 50 to 0%
18	Strong Click 2 - 80%	59	Transition Click 2 – 80%	100	Transition Ramp Down Long Sharp 1 – 50 to 0%
19	Strong Click 3 - 60%	60	Transition Click 3 – 60%	101	Transition Ramp Down Long Sharp 2 – 50 to 0%
20	Strong Click 4 - 30%	61	Transition Click 4 – 40%	102	Transition Ramp Down Medium Sharp 1 – 50 to 0%
21	Medium Click 1 - 100%	62	Transition Click 5 – 20%	103	Transition Ramp Down Medium Sharp 2 – 50 to 0%
22	Medium Click 2 - 80%	63	Transition Click 6 – 10%	104	Transition Ramp Down Short Sharp 1 – 50 to 0%
23	Medium Click 3 - 60%	64	Transition Hum 1 – 100%	105	Transition Ramp Down Short Sharp 2 – 50 to 0%
24	Sharp Tick 1 - 100%	65	Transition Hum 2 – 80%	106	Transition Ramp Up Long Smooth 1 – 0 to 50%
25	Sharp Tick 2 - 80%	66	Transition Hum 3 – 60%	107	Transition Ramp Up Long Smooth 2 – 0 to 50%
26	Sharp Tick 3 – 60%	67	Transition Hum 4 – 40%	108	Transition Ramp Up Medium Smooth 1 – 0 to 50%
27	Short Double Click Strong 1 – 100%	68	Transition Hum 5 – 20%	109	Transition Ramp Up Medium Smooth 2 – 0 to 50%
28	Short Double Click Strong 2 – 80%	69	Transition Hum 6 – 10%	110	Transition Ramp Up Short Smooth 1 – 0 to 50%
29	Short Double Click Strong 3 – 60%	70	Transition Ramp Down Long Smooth 1 – 100 to 0%	111	Transition Ramp Up Short Smooth 2 – 0 to 50%
30	Short Double Click Strong 4 – 30%	71	Transition Ramp Down Long Smooth 2 – 100 to 0%	112	Transition Ramp Up Long Sharp 1 – 0 to 50%
31	Short Double Click Medium 1 – 100%	72	Transition Ramp Down Medium Smooth 1 – 100 to 0%	113	Transition Ramp Up Long Sharp 2 – 0 to 50%
32	Short Double Click Medium 2 – 80%	73	Transition Ramp Down Medium Smooth 2 – 100 to 0%	114	Transition Ramp Up Medium Sharp 1 – 0 to 50%
33	Short Double Click Medium 3 – 60%	74	Transition Ramp Down Short Smooth 1 – 100 to 0%	115	Transition Ramp Up Medium Sharp 2 – 0 to 50%
34	Short Double Sharp Tick 1 – 100%	75	Transition Ramp Down Short Smooth 2 – 100 to 0%	116	Transition Ramp Up Short Sharp 1 – 0 to 50%

Fig 26: DRV2605 effects list
From Adafruit website

3) Improved voice-coiled actuators : the Haptuator

Because being limited to one single frequency may be a severe limitation for haptic research, some voice-coil actuators were designed to allow a certain bandwidth.

Instead of a spring, two rubber membranes are used to maintain the magnet of the « haptuators » developed by TactileLabs (Fig. 27). Amongst many other optimizations described in [Yao & Hayward, 2010], this results in a quite flat frequency response beyond the resonance frequency with high acceleration amplitudes (Fig. 28). However, the price is two orders of magnitude higher than for common ERM or LRA.

Here are its typical features :

Price	Diameter	Rated current	Acceleration	Latency	Control
200 $	10mm	500 mA	3g@3V	20-30ms	AC

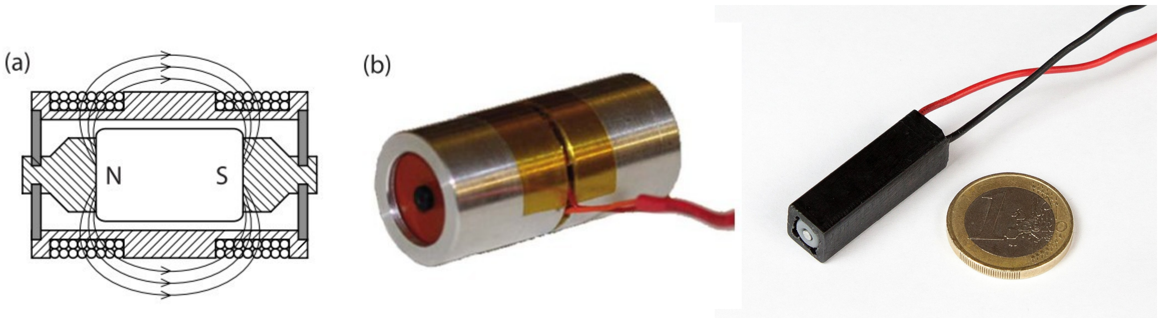


Fig 27 : Haptuator models
From TactileLabs website

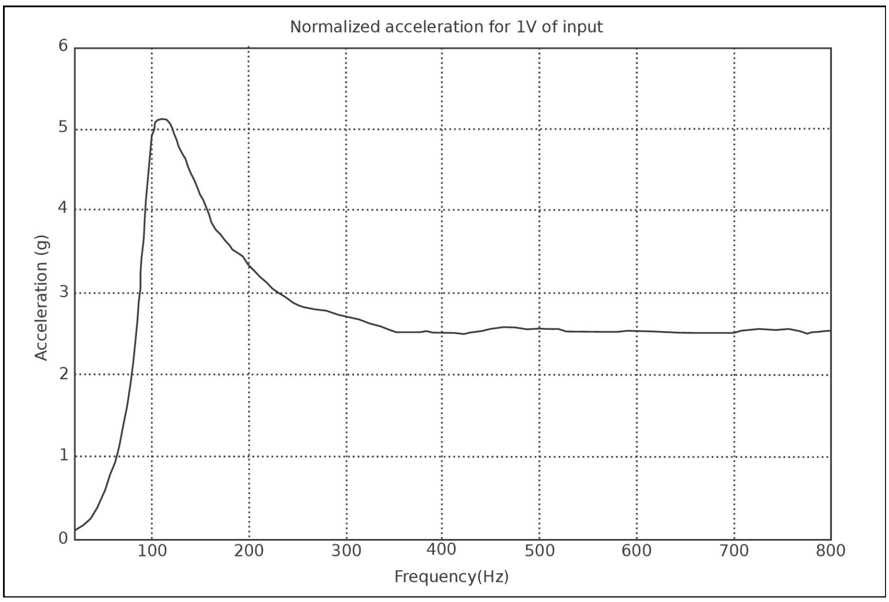


Fig 28 : Frequency response for Haptuator Mark II
From TactileLabs website

4) Other vibration technologies

Piezoelectric elements are sometimes mentioned as potential vibrotactile actuators, as they have extremely low latencies (less than 10ms) and independent frequency, amplitude and phase control. However, information about their acceleration amplitude and price are often unclear. Coupling between displacement and voltage would also probably be a limitation to consider, as well as high voltage and complex driving electronics requirements.

Pneumatic technologies are seldom mentioned as haptic technologies, although some prototypes were developed for fighter pilots suits [McGrath, 2000]. According to [McGrath et al., 2008], « pneumatic tactors require an AC signal, typically a square wave, in the 20 to 50 Hz range, with a current up to 100 mA that is sent to a miniature solenoid valve assembly. Frequency can be independently varied over the stimulus range. In addition, the pneumatic tactor system needs a pressurized air source. » The main disadvantage for vibrotactile applications seems to be the poor spatial resolution and the devices complexity [Pasquero, 2006, Appendix].

IV. Experiments

1) Preliminary tests

(a) Body sites

Preliminary tests were conducted to test several vibrators and identify easy-to-find body sites suitable for eliciting a global body response (Fig. 29 and 30). Several body sites were tested according to the literature [Wierzbicka et al., 1998] [Ceyte et al.,2006] [Strupp et al., 1998] : the Achilles tendon (AT), the Tibialis Anterior tendon (TAT), the Sterno-cleido-mastoidus muscle, and various sites on the Trapezius muscle, eventually also vibrating the Splenius and the Semispinalis Capitis.

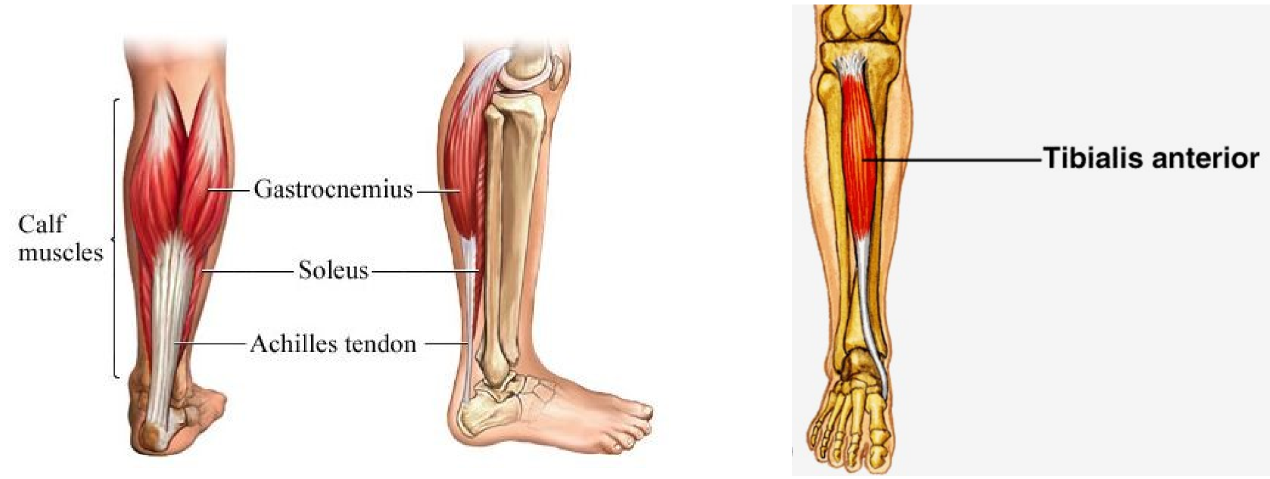


Fig 29 : Ankle sites : Achilles tendon and Tibialis Anterior tendon

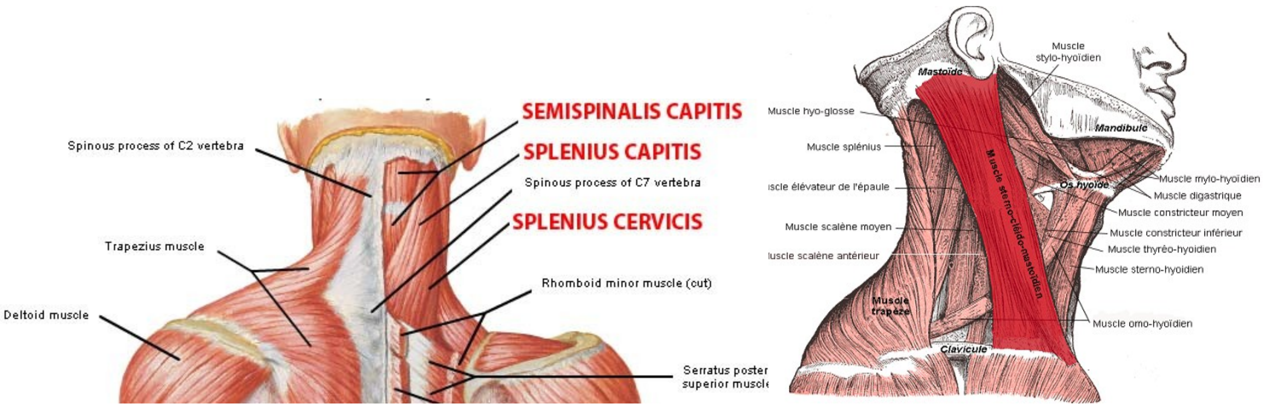


Fig 30 : Neck sites : Trapezius, Splenius and Sterno-cleido-mastoidus tendon

(b) Motor choice

Seven different vibrators from the Precision MicroDrives catalog were tested. The feature comparison is shown in Fig. 31. The 310-112 and the 306-101 were chosen for their high amplitude (~ 1g) at 120 Hz and their small dimensions. The 325-100 and the 324-401 models were chosen despite of their big size because of their very high amplitude (> 1g) at 90 Hz. The 307-001 was chosen as it offers a good trade-off between size and amplitude. The 310-003 was chosen despite of its small amplitude because of its pancake shape.

The C10-100 LRA were also tested with the DRV2605L breakout from Adafruit.

Name	310-003	310-004	306-117	306-101
Max start voltage	0.9 V	1.2 V	1 V	1.4 V
Freq Range	110-180 Hz	110-160 Hz	100-240 Hz	120-200 Hz
Amplitude Range	0.4-1.1 g	0.37-0.8 g	0.4-2.6 g	1.2-3 g
Best regime	0.4g@110Hz@0.9V	0.37g@110Hz@1.2V	0.5g@100Hz@1V	1.2g@120Hz@1.5V
Dimensions (mmxmm)	10x3.4	10x3.4	7x25	6x10.3

Name	307-001	310-112	324-401	325-100
Max start voltage	0.8 V	0.8 V	2.1 V	1.5 V
Freq Range	60-120 Hz	60-160 Hz	25-95 Hz	40-90 Hz
Amplitude Range	0.6-1.7 g	0.2-1.6 g	0.1-2.4 g	0.2-1.2 g
Best	1g@80Hz@1.1V	0.75g@120Hz@1.7V	1.4g@80Hz@9V	0.95g@80Hz@3V
Dimensions (mmxmm)	7x16.6	10x13	24x13	24x30

Fig 31 : ERM vibrators comparison
Six motors (in green) were selected for their high amplitudes between 80 and 120Hz
(see performance curves in appendix)

The DRV2605's haptic waveforms were tested with the C10-100 LRA, but the amplitudes were much weaker than with any ERM motor and were not suitable for any muscle activation. However, the audio control with an amplifier was not tested.

(c) Hardware design

A custom electronic device (Fig. 32 and 33) was built to control vibration motors with simple commands over a serial port. The purpose was to be able to easily switch between motors and to control several ones at a time.

As any DC motors, ERM should be powered from an external source and set in parallel with a flyback diode. For simplicity, an ULN2803A Darlington transistor array was used to power up to 8 motors from a 5V external source thanks to a standard female barrel jack connector.

Solderless connectors were added to each motor and on the board so the motors could be quickly changed (Fig. 34 and 35).

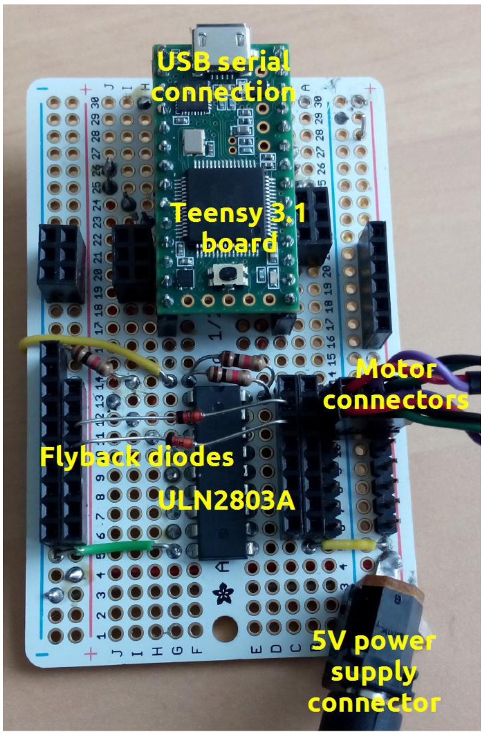


Fig 32 : The protoype board

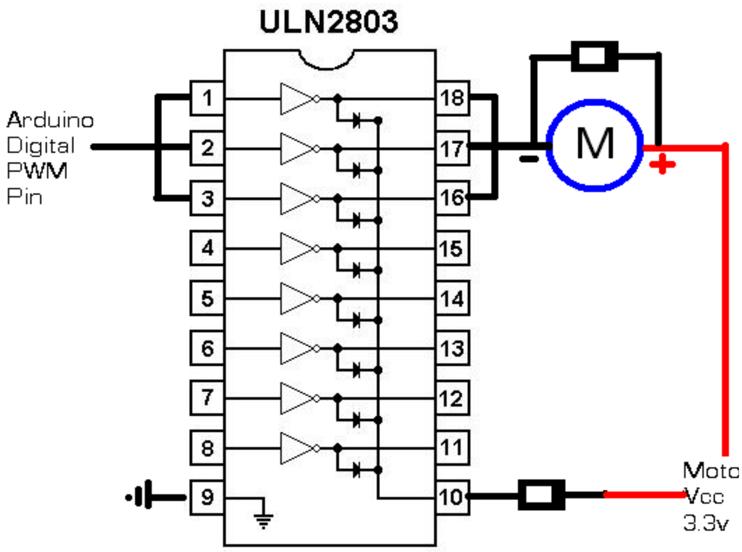


Fig 33 : ULN2803 schematic use

Fig 34 : 325-100 motor customization

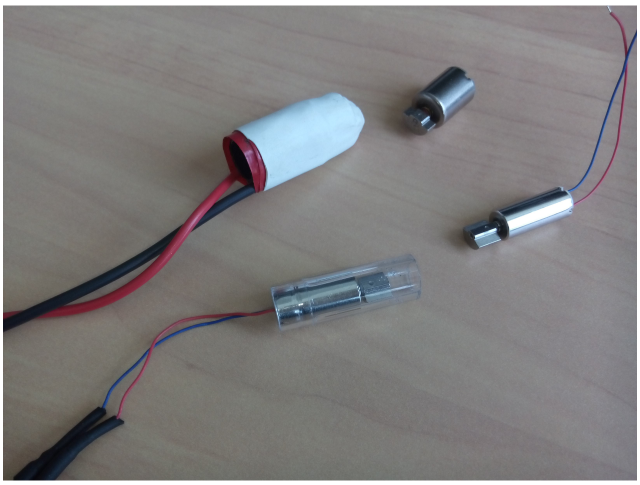


Fig 35 : 310-112 and 307-001 customization

A Teensy 3.1 Arduino-compatible board was used to control the motors via PWM signals sent to the transistor array, according to specific serial commands received over a serial USB connection. The arduino code was meant to remain a basic executor and to be kept as simple as possible.

The serial protocol used consisted in three-bytes commands : one entry byte, one index byte and one value byte. The entry byte should always be 255. The index byte indicated the motor index from 0 to 7. A 255 value for the index byte would indicate that all the motors are concerned. The value byte corresponded to the PWM value to send to the transistor, resulting in a 0 to 5V voltage at motor terminals. As the Arduino API allows only 256 different PWM values, the value byte could be directly used. It had to be inverted however, as the ULN2803A consist in NPN transistors : a high output is obtained was a low input and a low input is obtained with a high input.

(d) Experimental issues

For each motor and different frequencies, with eyes closed or open, each site was vibrated for about 10 seconds, followed by a rest period of 5 to 10 seconds. The vibrator was placed manually. Subjects were asked to describe their sensations and their body orientation was supervised.

The tests revealed several experimental difficulties. First of all, the vibrator should be firmly attached to the tendon to transmit the vibration properly, which requires specific attachment depending on the vibrator's shape. Whereas cylindrical shapes are quite convenient, disc shaped motors like the 310-003 and the 324-401 were not usable in practice as their flat part does not transmit well their radial vibration. Besides, the big 325-100 was found to be much easier to attach with a precise contact point than the three small cylinder shaped vibrators.

If the positioning at ankle was quite easy, no placement was found on the neck to be efficient on a majority of subjects. This is consistent with the literature, which indicates weaker effects for neck stimulation compared to ankle stimulation [Wierzbicka et al., 1998], and a difficulty to know precisely which muscles are vibrated because of neck musculature's complexity [Strupp et al., 1998] [Ceyte et al.,2006]. For most neck vibration experiments, vibrator's best placement is determined individually [Strupp et al., 1998] and/or subjects are selected for their sensitivity [Karnath et al., 2002], which is representative of the difficulty to establish a uniform and standardized technique to vibrate this region efficiently.

Because of these placement difficulties, high vibration amplitudes were needed to compensate. This resulted in strong, highly unpleasant vibrations of the head. Also, attaching the vibrator on the neck with enough pressure was not possible without a specific textile piece. For all these reasons, it was decided to focus on ankle stimulation only.

Although easier, placement at ankle requires a bit of experience to be really efficient. Any deviation in motor placement may bring up unwanted regions to be vibrated. Placing the vibrator alongside the AT appeared to produce variable and often weak effects; the most simple and effective placement was clearly behind the ankle, with the vibrator touching the tendon only. Asking the subject to raise the big toe makes the TAT visible and indicates the best place for the motor (see Fig. 36).

With these two methods, I was able to get a precise a reproducible placement at ankle.

Fig 36 : Best placements for vibrators at ankle

Another issue was the change in frequency when the vibrator is pressed against the skin. ERM vibrators are actually open-loop devices and their performances change slightly depending on the load.

For instance, according to the datasheet, the 307-001 vibrates at 80Hz with 1g amplitude under 1V, which is promising for muscle vibration purpose, but in the end it was found to be inefficient.

As a precise frequency and amplitude monitoring would have been too complicated to implement, motors have been empirically tested rather than methodically. It was found that the 325-100 ERM, under about 4V, was clearly the most effective ERM to elicit a TVR and induce a body sway. It was thus chosen as the only vibrator used for the experiments.

Measurements have been conducted later to determine the corresponding frequency. Some voltage monitoring were attempted, but without convincing results. I finally decided to analyze the motor sound with a simple pitch measurement, thanks to a microphone and a very basic Pure Data patch using the sigmund~ object (Fig. 37). Although the method was uncertain, the results were highly reproducible, and quite trustworthy as they confirmed my empirical findings according to the literature.

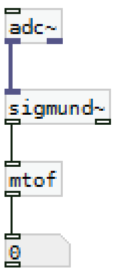


Fig 37 : The Pure Data Patch used for pitch analysis.
The number object indicates the fundamental frequency.

The 325-100 powered at 4V was found to vibrate around 80Hz (whereas this frequency is reached around 3v according to the datasheet), as the best stimulation frequency is generally estimated between 70 and 90Hz according to authors.

The 307-001 was found to vibrate around 100 Hz under 1V when attached to the tendon (about 195Hz when free). This could explain its poor results for eliciting a TVR, given the fact that the amplitude may not be as high as 1g.

Although it would have been very instructive, amplitudes were not measured because of instrumentation's complexity. However, these late frequency measurements let me notice that the 325-100 was still effective at lower voltage (around 3V and 70Hz), which reduce its noise and its uncomfortable vibrations.

Once we had establish a muscle vibration technique eliciting clear and strong body reactions, namely using the 325-100 at 4V at AT or TAT, we wanted to evaluate the reproducibility and the variability of these effects.

2) Experimental evaluation

(a) Materials and methods

Stimulation conditions

In addition to the previously described vibration sites, two control sites were added, located in the hollows on each side of the AT. These sites were found to have weak but also variable effects during preliminary tests.

The vibrators were placed according to two different configurations : AT and TAT, or the two control sites. For half of the subjects, four stimulation conditions were performed out in the first configuration, then in the middle of the experiment vibrators were placed in the second configuration and all conditions were performed again. For the other half, the second configuration was used first.

The 325-100 vibrators were controlled with a step command at 4V, making them vibrate around 80 Hz after a ramp-up period of 50 to 300 ms.

For each subject, 8 sessions of 50 seconds were performed : 10 seconds rest, 10 seconds stimulation with one motor, 10 seconds rest, 10 seconds stimulation with the other motor, then 10 seconds rest. The order the motors were used was inverted for half of the sessions, and the subject had their eyes closed or open : these two binary possibilities formed the four stimulation conditions for each of the two motor configurations.

Hardware and software set-up

A Wii Balance Board (WBB) was used to monitor and record body lean over time. This device gives the mass supported by each of its four pressure sensors located at its corners. The sum of this four measures gives the total mass of the person. Providing that the person is placed at the center of the board, this mass repartition is representative of the center of pressure's location. Assuming that the person stands straight, a shift in his center of pressure indicates a body tilt.

BlueSoleil software was used to handle Bluetooth drivers and detect the WBB. GlovePIE software was used to retrieve WBB data 100 times per second and send them to a custom Python software using the OSC protocol (Fig. 38). WBB data consisted in five values : the four mass values measured at each corner of the board plus the total mass value.

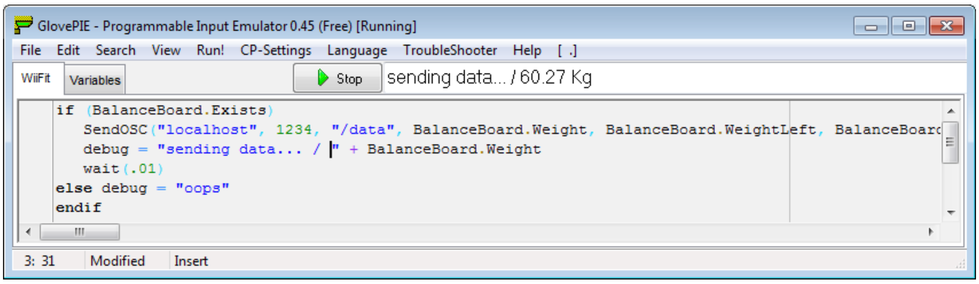


Fig 38 : The GlovePIE script used to retrieve data from Wii Balance Board

From these five measurements given by the WBB, two quantities were computed. The “front/back ratio” was defined as the difference of the two front values with the two back values, divided by the total mass value. Its value was therefore 1 when the subject was on his toes and -1 when on the heels. The “right/left ratio” was defined similarly to be equal to 1 when the subject was on the right foot and -1 when on the left foot. The total mass (in kg divided by 100 for simplicity) was also recorded to detect any eventual measurement problems.

A custom Python software (using PyQtGraph framework, see Fig. 39) was used to conduct the experiment, i.e. record the data and control the vibrators according to experiment timeline. During a session, a hundred times per second, an OSC message containing the WBB data was received. These data were processed to get the three quantities described before, which formed with the activity of the two motors a set of five values, associated with current time. All data were saved in CSV or NPZ files to be analyzed later with another custom Python software.

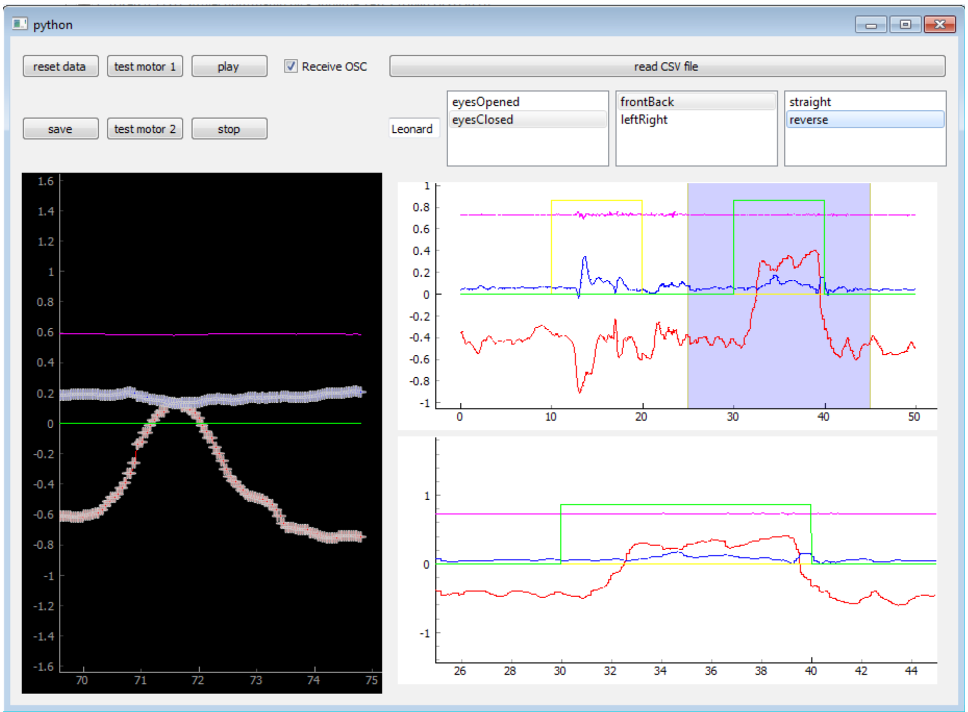


Fig 39 : The custom Python software used to conduct the experiment
Left : real time monitoring of the tilt ratios
Right : display of the previous session with a local zoom
Plotted data are : front/back ratio (red), right/left ratio (blue),
motor commands (green and yellow), total mass (pink)

Protocol

15 volunteer subjects (13 men, 2 women) with no particular medical background participated in the experiment. They were informed they were about to participate to a perceptual experiment, and that they could ask any questions at the end. After having removed their shoes and put an ankle brace on the right foot, they were invited to stand on the board (see Fig. 40). The given instructions were the following : to relax their body and to keep their arms alongside, to fixate a point straight ahead when not closing the eyes and to avoid improper movements during the sessions. After each sessions, subjects were also asked to report any "particular sensations". Attention was payed, to the extent possible, not to suggest what kind of sensations the vibrations could produce. When a perceived motion was reported, precisions were asked about its direction and its type (imbalance, displacement, fall, etc...).

Post treatment

Each session measurement of two stimulations over 50 seconds were split in two stimulation measurements of 30 seconds each, the 10 seconds rest period between the two stimulations being part of the two measurements (pre-stimulation period for the first one, post-stimulation period for the second one).

For each stimulation measurement, the average rest tilt ratio was computed and subtracted to the measurement to get tilt shift from rest position. As some unwanted movements occurred sometimes in the first seconds, this average value was computed only during the second half of the rest period (from 5 to 10 seconds).

In the following, quantitative results will thus refer to tilt shift.

Fig 40 : Experimental set-up : example of forward body tilt

(b) Results

TAT stimulation induced, for almost every subjects, a forward body tilt of various amplitude, generally about 5°. Three different phases were generally identifiable in the response curves : a transitory phase with a rapid tilt, a constant phase with stabilized position around a mean value, and a comeback phase with a rapid backward tilt.

Despite a notable variability among the subjects, the transitory phase and the comeback phase were typically of 1 to 2 second. A typical reponse is shown in Fig. 41.

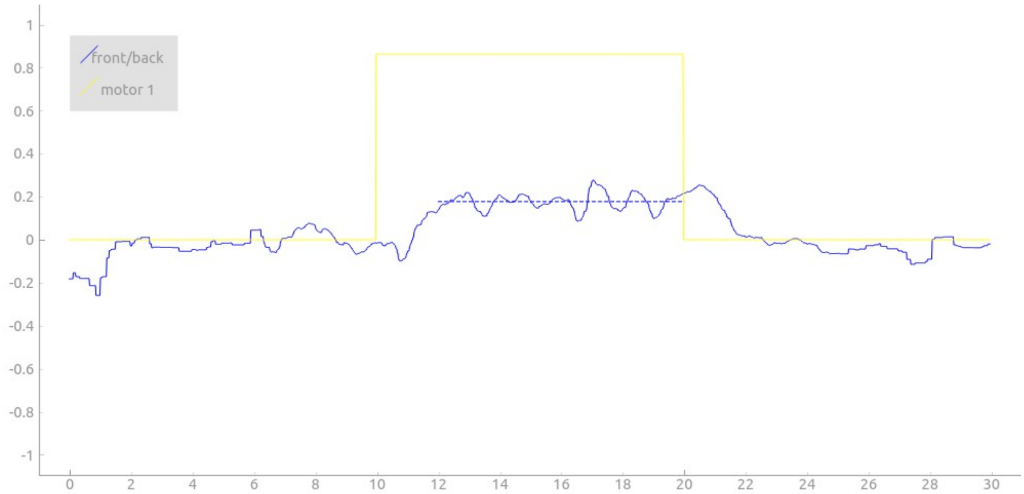


Fig 41 : Typical response for a TAT stimulation
The “front/back” tilt ratio shift (in blue) increases suddenly about one second after the motor onset (in yellow), to reach over about two seconds a constant phase where it oscillates around a mean value (in dot lines). About one second after the motor offset, it comes back around zero over about a second.

The subjects often perceived only the final backward movement, even when the forward movement was clearly visible for an external observer. Whether it was perceived or not, the movement seemed to be reflexively refrained in about half of the cases. Some subjects reported that they instinctively resisted to the forward movement, whereas some were obviously resisting it without reporting any particular sensation.

In some cases, the average final position was different from the average start position, the shift being always in the opposite direction to the stimulation tilt (Fig. 42).
The “right/left ratio” remained remarkably stable for every stimulation (Fig. 42).

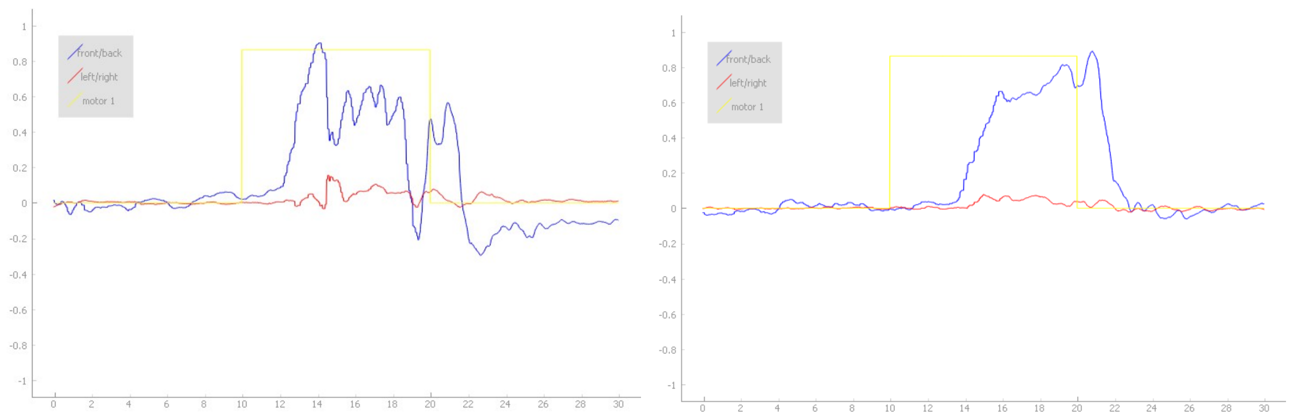


Fig 42 : Examples of strong reactions to TAT stimulation
Left : strong oscillations during the constant phase, backward shift aftereffect.
Right : slow but strong tilt shift, no aftereffect.

AT stimulation gave very similar results, except that the tilt was forward and amplitudes were roughly two times lower.

The stimulation of the two neutral sites had no effect except in two cases of strong backward tilt (similar to an AT stimulation).

The verbal reports mentionned mainly two types of sensation : an unvoluntary leaning or an imbalance feeling. One subject reported a segmental kinesthetic illusion : his leg seemed to move aside like the foot was sliding. No vection feeling was reported.

The average tilt shift value during the constant phase was considered as representative of the reaction's amplitude. These values were first separated in four sets according to stimulation site. A Shapiro-Wilk test indicated a non-parametric distribution for two of the four sets ("front" and "right", p-value < 0.0001). The average values of these four sets are given in Fig 43. Compared to the "back" condition, the "front" condition resulted in amplitudes in average two times larger in absolute values; the average value was about three times smaller for the "right" condition and about ten times smaller for the "left" condition.

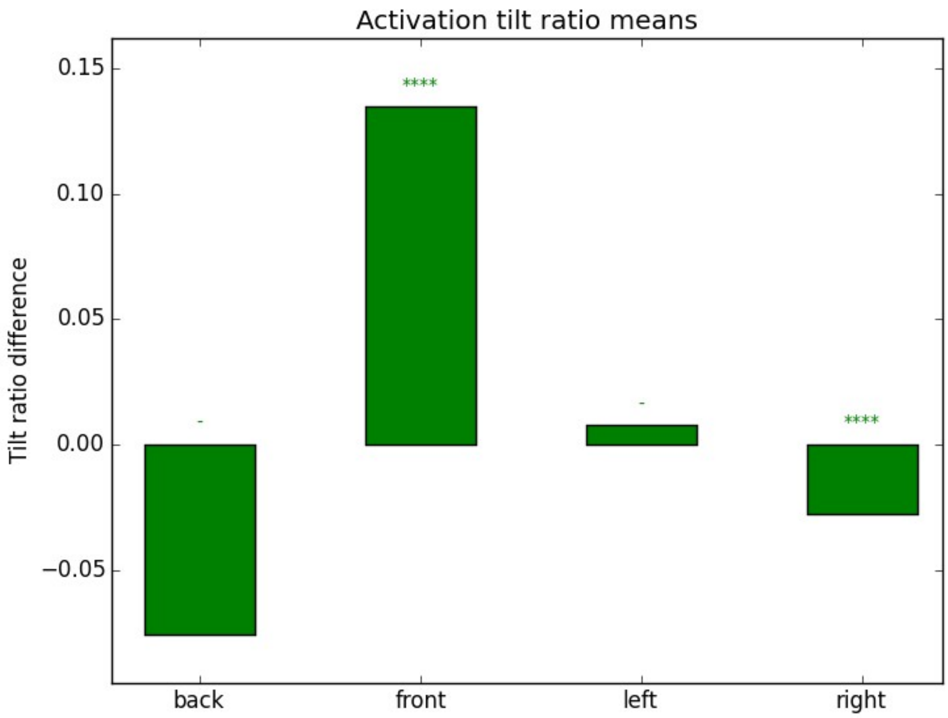


Fig 43 : Mean tilt ratio shifts during the constant phase according to stimulation site.
Stars indicate the results of the Shapiro-Wilk test for each set.

Each set was then subdivided in two subsets according to the "eyes" condition (whether the eyes were closed or not during the stimulation). The subsets from the two non-parametric sets were also considered as non-parametric by a Shapiro-Wilk test. Except for the "right" condition, the "eyes closed" condition resulted in larger average amplitudes, as shown on Fig 44. A non-parametric Wilcoxon test was performed between the two subsets for each stimulation site , which revealed that this difference was significant only for the "front" condition.

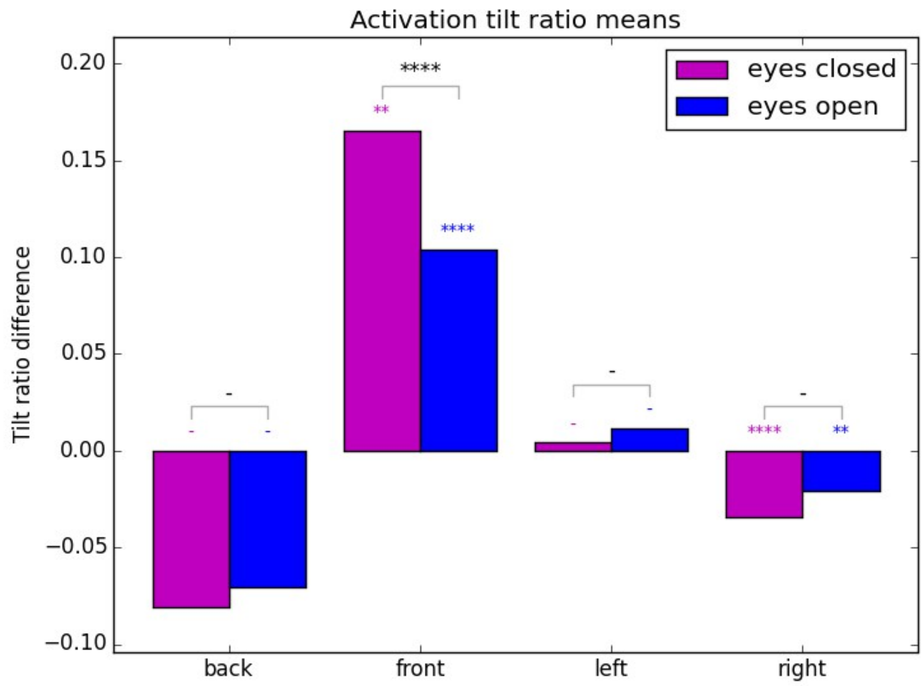


Fig 44 : Mean tilt ratio shifts during the constant phase
according to stimulation site and the eyes condition.
Colored stars indicate the results of the Shapiro-Wilk test for each subset,
black stars indicate the results of the Wilcoxon test.

(c) Discussion

The effect of the ankle vibration clearly differed according to stimulation site. TAT and AT induced strong tilt shifts in specific directions, which allows to consider them as reliable causal effects rather than random and unpredictable reactions.

The induced tilt was generally not perceived by the subjects, especially when the amplitudes were low. The fastest movements, namely the final comeback tilts and the induced tilts with the largest amplitude, were almost systematically perceived. Interestingly, they were of a few centimeters per second, which is just above the vestibular perception threshold. These results suggest that although the proprioceptive system is responsible for inducing the movement, it does not play its usual perceptive role for it, and that only the vestibular system allows to perceive it clearly.

In some cases, AT or TAT stimulation resulted in a noticeable aftereffect on rest position, which was systematically a shift in the opposite direction. This evokes a rapid compensatory adaptation, often reported in posture mechanisms. However no clues were found about the factors causing these aftereffects.

Their possible consequences on further bodily reactions were not identified. Results were splitted in two sets whether the stimulation was the first or the second in the session, but no noticeable difference was noticed between these two conditions.

The difference between amplitudes of the "front" and the "back" conditions may be simply due to anatomical limits : the maximum tilt before falling is about two times larger forward than backward. The relative high score of the second neutral site, namely the "right" condition, is due to a few large amplitude reactions, very similar to those of a AT stimulation. As this site was close to the AT, it is very likely that an accidental contact was the cause of these anecdotical effects.

The difference between the two "eyes" conditions was expected, as all subjects reported stronger effects with eyes closed. However the possible interaction between proprioceptive and visual inputs was one of the purposes of the experiment. The difference was significative only the "front" condition, which was also the condition with the largest amplitude. This is coherent with the findings of [Adamcova & Hlavacka, 2007], which proposed that vision has only a regulation role on posture, that one can model by a simple negative proportional retroaction. Therefore, large amplitudes result in a strong regulation effect, whereas small or slow movements will not be significantly affected by vision.

3) Combination with a visual stimulus

Preliminary tests were conducted for a second experiment focusing on the interaction between vibration-induced tilt and visual input inducing vection. The purpose was to determine if a synergy was possible between these two types of stimuli, i.e. if their combined effects could enhance each other rather than simply add.

The dynamic of the transitory phases in the previous experiment were examined, and it was noticed that the beginning of the movement was quite smooth and incurved whereas its end was pretty sharp, so that one could model the shape of the tilt movement with a quadratic curve. Although no acceleration feeling was reported by the subjects, this quadratic-like evolution of the body tilt seemed interestingly fitting a constant acceleration context. One can thus assume that despite the vibration stimulation only is not sufficient to produce vection, it may enhance the strength or the compellingness of a constant acceleration illusion induced by another stimulus. This hypothesis was chosen to be tested in the preliminary tests.

Three different ankle stimulations were considered : vibration of the AT, vibration of the TAT, and vibration of both tendons. Because of the bias due to the strong noise and physical sensation produced by vibrators activity, vibration of both tendons was chosen as "neutral stimulation" instead of no vibration, as it the effects of vibrating agonist muscles with the same stimulus cancel [Gilhodes et al., 1986]. The vibrators were activated with a step command resulting in a 80 Hz vibration, like in the first experiment.

The stimulus duration was of 4 seconds, as only the transitory phase was considered here.

A linear optical flow of white dots was implemented in Unity3D and rendered via a head-mounted display. This solution was chosen because vision-induced vection is known to be stronger when the peripheral visual field is stimulated [Delorme & Martin, 1986]. The immersive functionality of using the head tracking to simulate a virtual reality environment was not used. The visual stimulus was synchronized with the vibration stimulus, so that its duration was of 4 seconds and that they were triggered together.

The three visual conditions were : constant acceleration (5 m/s², from 0 to 20 m/s), constant speed (at 20 m/s), and constant decceleration (-5 m/s², from 20 to 0 m/s).

The 8 stimulation conditions were the possible combinations between these two sets of three conditions, except the constant speed with double vibration. After each stimulation, subjects were asked to report direction and intensity (on a 0-10 scale) of the movement globally evoked.

However, these tests revealed that the two kinds of stimuli produced two distinct kinds of sensations that could not be intuitively merged. Subjects were confused about what they had to describe and obviously tend to focus on the physical sensations related to the body tilt and to neglect the more common visual vection effect.

It was concluded from these tests that pyschophysics experiments require a tighter methodology when assessing the combination two different modalities, as the tasks or questions asked to the subjects has to keep their simplicity whereas the studied perceptions may be way more complex. Even a forced-choice alternative may be not easy to formulate. Nevertheless, a user experience rating remains relatively easy to elaborate.

Besides, a linear vection stimulus may not be an appropriate visual stimulus to address the initial question. As explained in the discussion of [Adamcova & Hlavacka, 2007], the reflexive tilt induced leg muscle vibration is due to a perturbation of verticality's perception. Therefore, if there is any possibility of combination with other artificial motion sensation, it is more likely with rotative than linear motion. The fact that subjects report a “forward” or “backward” lean is not significant as this is the natural way to describe a rotation around the ankles.

It is highly probable that ankle stimulation could enhance global body pitch in an immersive experience. Short tests were conducted and gave promising results, but the user experience evaluation was not conducted because of the lack of time.

The optical flow was replaced with a first person view video of a funfair giant swing, and the vibration was synchronized with the swing's oscillations. This set-up was tried only with a few people, but all of them reported enhanced sensations and an increased immersivity.

Conclusion

The perception that we have of our body motion and orientation is inherently multimodal : vestibular and visual informations are predominant, but contributions from the kinesthetic and tactile senses are also taken in account, depending on the context. Each of these senses have their own limits and can be tricked to elicit various illusions.

Except for muscle vibration, the several kinesthetic illusion techniques that can be found in the literature are recent proposals, limited to what can be considered as preliminary studies. Feet stimulation seems to be the most promising one, with diverse and unexpected effects, as the receptors in the plantar sole appear to play various roles in the global balance and motion perception mechanisms.

Muscle vibration is a relative well-known technique, but its effects were mainly studied from a medical point of view, and the question of its applications in other fields does not seem to have been addressed yet. Of course, some technical issues still strongly limit its development and challenges have to be met : for instance, developing an easy-to-set-up actuator producing reliable and generalisable effects despite of the anatomic diversity.

As it is the oldest and most well-known method to elicit artificial motion sensations, muscle vibration was chosen to be experimentally tested during this internship. Vibrating various muscles via their tendons at neck or ankle alters the subject's verticality perception and elicits specific reflexive whole-body tilts; kinesthetic illusions occur when these movements are hindered. As this impediment requires a heavy set-up, that seems by the way hardly compatible with virtual reality or entertainment ergonomics, we chose to focus on the reflexive movements, which is seldom the case in the literature.

Contrary to kinesthetic illusions, were a movement is perceived as the body is still, these body tilts are real movements, but not necessary clearly perceived by the subjects. Despite a great inter-subject variability in movement amplitudes, most subjects had the expected whole-body reaction according to stimulation site. The question of reproducibility is likely limited to the technical difficulty of stimulating correctly the muscle in question. Visual cues were found to have a regulation role, consistently with the literature.

Unlike ankle stimulation, neck stimulation also allows for lateral movement and does probably not require a standing position to produce kinesthetic effects. However it is much more delicate to set-up and for this reason, it was only tested during preliminary tests. A better tuned actuator and experience in muscle stimulation should allow for exploring these possibilities.

The combination between muscle vibration and a visual stimulus providing additionnal motion informations was only briefly experimented because of a lack of time. Although such an experimental study poses difficult methodological questions, the various results obtained during this study suggest that pitch sensations during a multimedia experience could be easily and strongly enhanced with muscle vibration.

The use of muscle vibration to produce or enhance motion sensations raises three different problematics that should be addressed in future work : developping an easy-to-use and easy-to-set-up actuator, able to efficiently but "discreetly" stimulate the right muscle ; identify factors explaining the inter-subject variability in body tilt amplitudes ; evaluate and quantify the interaction between visual and proprioceptive cues in the perception of body pitch.

Bibliography

Adamcova, N., & Hlavacka, F. (2007). Modification of human postural responses to soleus muscle vibration by rotation of visual scene. *Gait & posture*, *25*(1), 99-105.

Albert, F., Bergenheim, M., Ribot-Ciscar, E., & Roll, J. P. (2006). The Ia afferent feedback of a given movement evokes the illusion of the same movement when returned to the subject via muscle tendon vibration. *Experimental Brain Research*, *172*(2), 163-174.

Calvin-Figuière, S., Romaiguère, P., & Roll, J. P. (2000). Relations between the directions of vibration-induced kinesthetic illusions and the pattern of activation of antagonist muscles. *Brain Research*, *881*(2), 128-138.

Calvin-Figuière, S., Romaiguère, P., Gilhodes, J. C., & Roll, J. P. (1999). Antagonist motor responses correlate with kinesthetic illusions induced by tendon vibration. *Experimental Brain Research*, *124*(3), 342-350.

Ceyte., H., Cian, C., Nougier, V., Olivier, I., & Roux, A. (2006). Effects of neck muscles vibration on the perception of the head and trunk midline position. Experimental Brain Research, 170(1), 136–140.

Ceyte., H., Cian, C., Zory, R., Barraud, P. A., Roux, A., & Guerraz, M. (2007). Effect of Achilles tendon vibration on postural orientation. Neurosci Lett, 416(1), 71–75.

Cipriani, C., Dalonzo, M., & Carrozza, M. C. (2012). A miniature vibrotactile sensory substitution device for multifingered hand prosthetics. IEEE Transactions on Biomedical Engineering, 59(2), 400–408.

Cordo, P., Gurfinkel, V., Brumagne, S., & Flores-Vieira, C. (2005). Effect of slow, small movement on the vibration-evoked kinesthetic illusion. Experimental Brain Research, 167(3), 324-334.

Delorme, A., & Martin, C. (1986). Roles of retinal periphery and depth periphery in linear vection and visual control of standing in humans. *Canadian Journal of Psychology/Revue canadienne de psychologie*, *40*(2), 176.

DiZio, P., Lackner, J., & Champney, R. K. (2014). Proprioceptive adaptation and aftereffects. In Handbook of virtual environments : Design, implementation, and applications (2nd ed., pp. 835– 856).

Eklund, G. (1971). Some physical properties of muscle vibrators used to elicit tonic proprioceptive reflexes in man. Acta Societatis Medicorum Upsaliensis, 76, 271-280.

Farkhatdinov, I., Ouarti, N., & Hayward, V. (2013, April). Vibrotactile inputs to the feet can modulate vection. In *World Haptics Conference (WHC), 2013* (pp. 677-681). IEEE.

Gault, R. H. (1924). Progress in experiments on tactual interpretation of oral speech. *The Journal of Abnormal Psychology and Social Psychology*, *19*(2), 155.

Gilhodes, J. C., Roll, J. P., & Tardy-Gervet, M. F. (1986). Perceptual and motor effects of agonist-antagonist muscle vibration in man. *Experimental brain research. Experimentelle Hirnforschung. Experimentation cerebrale*, *61*(2), 395-402.

Gomez, S., Patel, M., Magnusson, M., Johansson, L., Einarsson, E. J., & Fransson, P. A. (2009). Differences between body movement adaptation to calf and neck muscle vibratory proprioceptive stimulation. *Gait & posture*, *30*(1), 93-99.

Goodwin, G. M., McCloskey, D. I., & Matthews, P. B. (1972). Proprioceptive illusions induced by muscle vibration: contribution by muscle spindles to perception? Science (New York, N.Y.), 175, 1382–1384.

Hagbarth, K.-E., and Eklund, G. (1966). Motor effects of vibratory muscle stimuli in man. In Muscular Afferents and Motor Control, pp. 177-186. Proceedings of the 1st Nobel Symposium, 1965, Sodergarn. Edited by R. Granit. Almqvist and Wiksell: Stockholm.

Hale, K. S., & Stanney, K. M. (2014). Handbook of Virtual Environments: Design, Implementation, and Applications, Second Edition. p. 173

Hayward, V., & Maclean, K. E. (2007). Do it yourself haptics: Part I. IEEE Robotics and Automation Magazine, 14, 88–104.

Johansson, R., Magnusson, M., & Fransson, P. a. (1995). Galvanic vestibular stimulation for analysis of postural adaptation and stability. IEEE Transactions on Biomedical Engineering, 42 (3), 282–292.

Jones, L. a. (1988). Motor illusions: what do they reveal about proprioception? Psychological Bulletin, 103(1), 72–86.

Jousmäki, V., & Hari, R. (1998). Parchment-skin illusion: sound-biased touch. *Current biology : CB*.

Karnath, H. O., Reich, E., Rorden, C., Fetter, M., & Driver, J. (2002). The perception of body orientation after neck-proprioceptive stimulation: Effects of time and of visual cueing. Experimental Brain Research, 143(3), 350–358.

Kavounoudias, A., Roll, R., & Roll, J. P. (1999). Specific whole-body shifts induced by frequency-modulated vibrations of human plantar soles. *Neuroscience Letters*, *266*(3), 181-184.

Kajimoto, H. (2013). Illusion of Motion Induced by Tendon Electrical Stimulation. In World haptics conference (pp. 555–558).

Lackner, J. R., & Levine, M. S. (1979). Changes in apparent body orientation and sensory localization induced by vibration of postural muscles: vibratory myesthetic illusions. *Aviation, space, and environmental medicine*.

Lackner, J. R., & Taublieb, A. B. (1984). Influence of vision on vibration-induced illusions of limb movement. *Experimental neurology*, *85*(1), 97-106.

Lackner, J. R., & DiZio, P. (2005). Vestibular, proprioceptive, and haptic contributions to spatial orientation. Annual Review of Psychology, 56, 115–147.

Leonardis, D., Frisoli, A., Solazzi, M., & Bergamasco, M. (2012). Illusory perception of arm movement induced by visuo-proprioceptive sensory stimulation and controlled by motor imagery. Haptics Symposium 2012, HAPTICS 2012 - Proceedings, 421–424.

McGrath, B. J. (2000). *Tactile instrument for aviation* (No. NAMRL-10-2000). NAVAL AEROSPACE MEDICAL RESEARCH LAB PENSACOLA FL.

Mcgrath, B., Mckinley, a, Duistermaat, M., Carlander, O., Brill, C., Zets, G., & Erp, J. B. F. Van. (2008). Chapter 4 – TACTILE ACTUATOR TECHNOLOGY by. NATO Science and Technology Organization, 1–12.

Matsue, R., Sato, M., Hashimoto, Y., & Kajimoto, H. (2008). “Hanger reflex” : AReflex Motion of a Head by Temporal Pressure for Wearable.

Mittelstaedt, H. (1995). Evidence of somatic graviception from new and classical investigations. *Acta oto-laryngologica. Supplementum*, *520 Pt 1*, 186-187.

Nakamura, T. (2014). Development of a Wrist - Twisting Haptic Display Using the Hanger Reflex. ,
3–7.

Nakamura, T., Nishimura, N., Sato, M., & Kajimoto, H. (2014, March). Application of hanger reflex to wrist and waist. In *Virtual Reality (VR), 2014 iEEE* (pp. 181-182). IEEE.

Naito, E., Ehrsson, H. H., Geyer, S., Zilles, K., & Roland, P. E. (1999). Illusory arm movements activate cortical motor areas: a positron emission tomography study. *The Journal of neuroscience*, *19*(14), 6134-6144.

Nilsson, N. C., Nordahl, R., Sikström, E., Turchet, L., & Serafin, S. (2012). Haptically induced illusory self-motion and the influence of context of motion. In *Haptics: Perception, Devices, Mobility, and Communication* (pp. 349-360). Springer Berlin Heidelberg.

Nordahl, R., Nilsson, N. C., Turchet, L., & Serafin, S. (2012). Vertical illusory self-motion through haptic stimulation of the feet. 2012 IEEE VR Workshop on Perceptual Illusions in Virtual Environments, PIVE 2012, 21–26.

Paillard, J., & Brouchon, M. (1968). Active and passive movements in the calibration of position sense *. The Neuropsychology of Spatially Oriented Behavior, 37–55.

Pasquero, J. (2006). Survey on communication through touch. Center for Intelligent Machines-McGill University, Tech. Rep. TR-CIM, 6(August), 1–28.

Quoniam, C., Hay, L., Roll, J. P., & Harlay, F. (1995). Age effects on reflex and postural responses to propriomuscular inputs generated by tendon vibration. *The journals of gerontology.*

Series A, Biological sciences and medical sciences, *50*(3), B155-B165.

Roll, J. P., & Vedel, J. P. (1982). Kinaesthetic role of muscle afferents in man, studied by tendon vibration and microneurography. *Experimental brain research. Experimentelle Hirnforschung. Experimentation cerebrale*, *47*(2), 177-190.

Roll, J. P., Vedel, J. P., & Ribot, E. (1989). Alteration of proprioceptive messages induced by tendon vibration in man: a microneurographic study. *Experimental brain research. Experimentelle Hirnforschung. Experimentation cerebrale*, *76*(1), 213-222.

Roll, J.-P., Albert, F., Thyrion, C., Ribot-Ciscar, E., Bergenheim, M., & Mattei, B. (2009). Inducing any virtual two-dimensional movement in humans by applying muscle tendon vibration. *Journal of neurophysiology*, *101*(2), 816-823.

Ruhl, A., & Lamers, M. H. (2011). Experiments with Galvanic Vestibular Stimulation in Daily Activities.

Sato, M., Matsue, R., Hashimoto, Y., & Kajimoto, H. (2009, September). Development of a head rotation interface by using hanger reflex. In *Robot and Human Interactive Communication, 2009. RO-MAN 2009. The 18th IEEE International Symposium on* (pp. 534-538). IEEE.

Stevens, J. C. (1979). Thermal intensification of touch sensation: further extensions of the Weber phenomenon. *Sensory processes*, *3*(3), 240-248.

Strupp, M., Arbusow, V., Dieterich, M., Sautier, W., & Brandt, T. (1998). Perceptual and oculomotor effects of neck muscle vibration in vestibular neuritis. Ipsilateral somatosensory substitution of vestibular function. Brain, 121(4), 677–685.

Tardy-Gervet, MF, & Severac-Cauquil, A. (1998). Effects of galvanic vestibular stimulation on perception of subjective vertical in standing humans (Vol. 86).

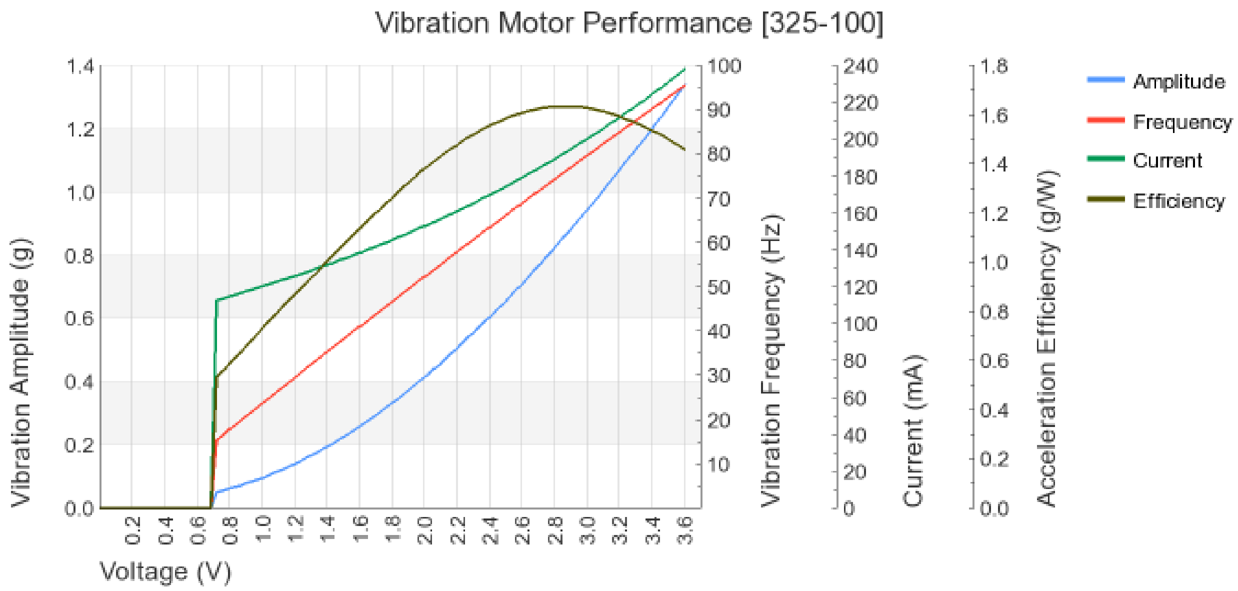
Thyrion, C., & Roll, J.-P. (2010). Predicting any arm movement feedback to induce three-dimensional illusory movements in humans. *Journal of neurophysiology*, *104*(2), 949-959.

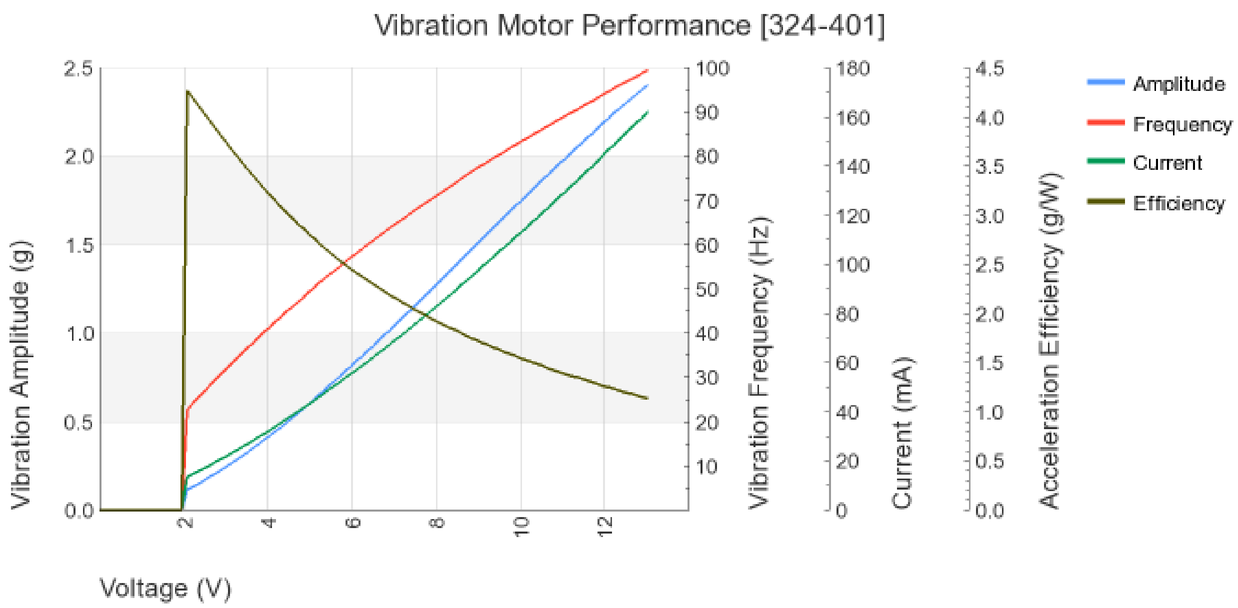
Wardman, D. L., Taylor, J. L., & Fitzpatrick, R. C. (2003, septembre). Effects of galvanic vestibular stimulation on human posture and perception while standing. The Journal of physiology, 551 (3), 1033–1042.

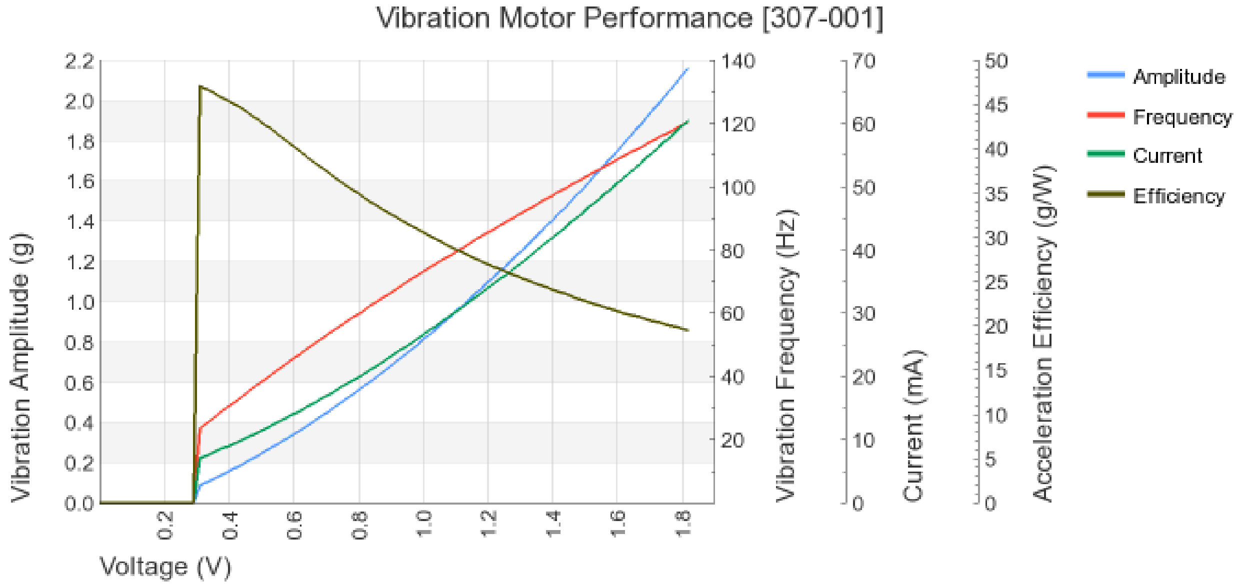
Wierzbicka, M. M., Gilhodes, J. C., & Roll, J. P. (1998). Vibration-induced postural posteffects. Journal of Neurophysiology, 79(1), 143–150.

Yao, H.-Y., & Hayward, V. (2010). Design and analysis of a recoil-type vibrotactile transducer. The Journal of the Acoustical Society of America, 128, 619–627. doi:10.1121/1.3458852

Appendix : ERM performance curves



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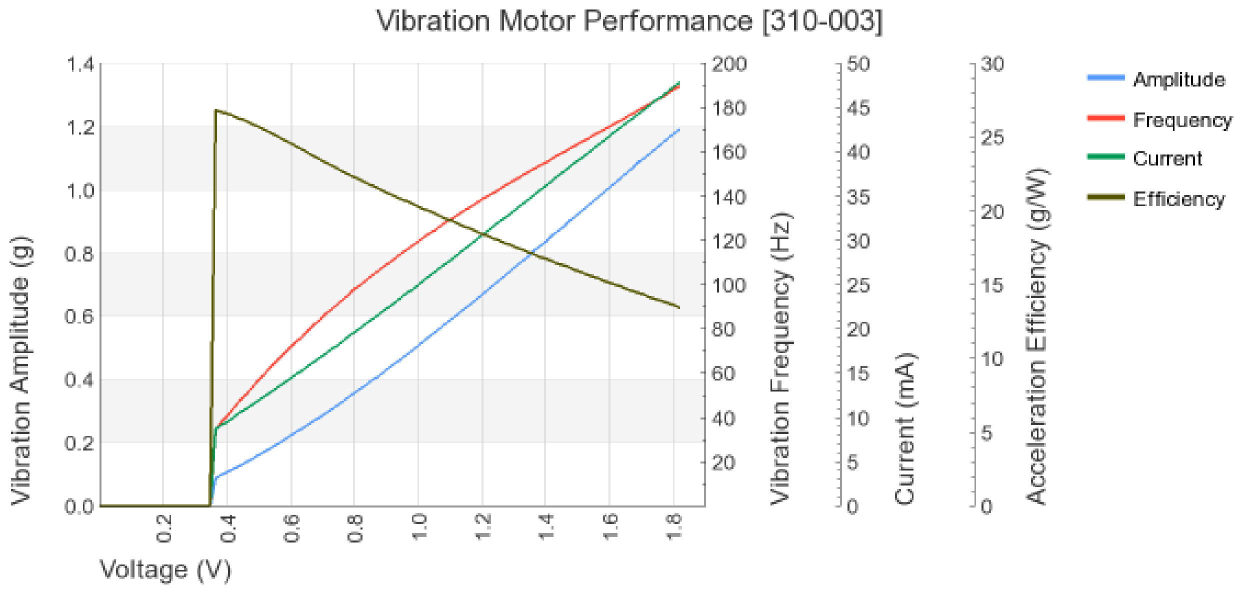
Voltage (V)
Vibration Frequency (Hz)
Current (mA)
Acceleration Efficiency (g/W)
Amplitude
Frequency
Current
Efficiency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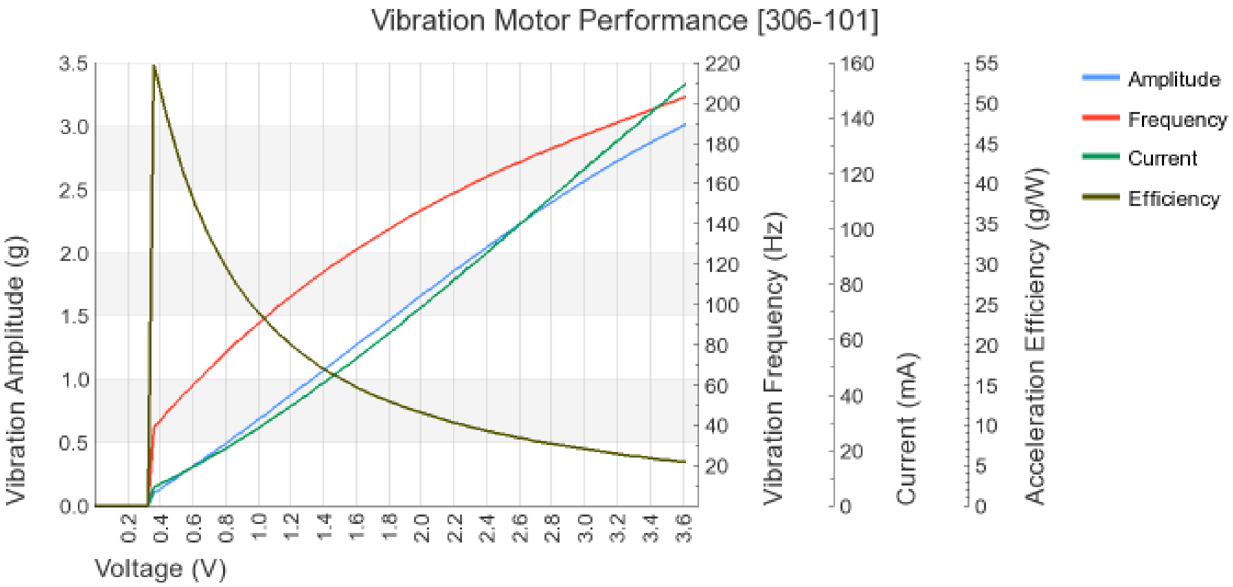
Vibration Amplitude (g)
Voltage (V)
Vibration Frequency (Hz)
Current (mA)
Acceleration Efficiency (g/W)
Amplitude
Frequency
Current
Efficiency


Vibration Motor Performance [306-101]
Vibration Amplitude (g)
Voltage (V)
Vibration Frequency (Hz)
Current (mA)
Acceleration Efficiency (g/W)
Amplitude
Frequency
Current
Efficiency