Vibrotactile Feedback and Stimulation in Music Performance

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Abstract

Vibrotactile feedback and stimulation can be used to convey information by means of specialized displays augmented with vibrating actuators. To achieve successful communications via the sense of touch, perceptual, technological and cognitive issues need to be taken into account in the design of these displays and of the tactile effects conveyed to the final user.

In this thesis we propose a systematic approach to the design of tactile displays and of tactile effects and icons in the context of music performance and practice: firstly, a perceptually-informed review of the function of vibrotactile feedback and stimulation in music performance is proposed, together with an evaluation of actuator technologies; secondly, in context, user-based evaluations of several vibrotactile-augmented displays are presented, which took place during the successful performance of real-world concerts and installations.

Résumé

Le feedback et la stimulation vibrotactile peuvent être utilisés afin de transmettre de l'information au moyen de dispositifs spécialisés rehaussés d'actionneurs qui vibrent. Afin d'établir une communication réussie à travers le sens du toucher, la conception de ces dispositifs et des effets tactiles transmis à l'utilisateur doit aborder les questions reliées à la perception, la technologie, et la cognition.

Dans cette thèse, nous proposons une approche systématique de la création d'outils, d'effets, et d'icônes tactiles dans le contexte d'interprétations et de pratiques musicales. D'abord, une revue de la littérature sur la fonction du feedback et de la stimulation vibrotactile en interprétation musicale est proposée, ainsi qu'une évaluation de différents types d'actionneurs. Finalement, nous présentons des évaluations de dispositifs vibrotactiles s'étant déroulées lors de concerts et d'installations artistiques, nous concentrant sur le jugement et la performance des utilisateurs.

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Contribution of Authors

Several results presented in this thesis have been published in the following publications:

- Chapter 4: *"Bowing a Vibration-Enhanced Force-Feedback Device"* - M. Giordano, S. Sinclair and M. M. Wanderley - Proceedings of NIME, 2012.

  My contribution to this paper is the design and assembling of a vibrotactile augmented handle for a force-feedback device. I conducted, together with the second author, measurement and analysis of acceleration data collected to characterize the behavior of the device in the interaction with the model of a bowed string.

- Chapters 2 and 3 *"Perceptual and Technological Issues in the Design of Vibrotactile-Augmented Interfaces for Music Technology and Media"* - M. Giordano and M. M. Wanderley, Proceedings of HAID, 2013.

  My contribution to this article is the conception of guidelines for the design and implementation of tactile-augmented devices for music performance and media, together with the definition of a three-fold taxonomy of tactile feedback and stimulation.

- Chapter 6 *"Vibrotactile Notification in Music Performance: A Prototype System"* - M. Schumacher, M. Giordano, M. M. Wanderley, and S. Ferguson - Proceedings of CMMR, 2013.

  My contribution to this work is the development of the hardware prototype of a tactile display and the design and development, together with the first author, of the tactile effects and mapping parameter space for a tactile notifier to be used in the performance with a live-electronics system.

- Chapter 5 *"Physical and Perceptual Characterization of a Tactile Display for a Live-Electronics Notification System"* - E. Frid, M. Giordano, M. Schumacher and M. M. Wanderley - In Proceedings of the ICMC and SMC, 2014.

  My contribution to this work is the physical characterization of ERM actuators by means of acceleration measurements, as well as the conception and design, together with the first author, of two experiment aimed at characterizing the vibrational behavior of these actuators as perceived by a user.

- Chapter 5 *"Design and Implementation of a Whole-Body Haptic Suit for "Ilinx", a Multi-sensory Art Installation"* - M. Giordano, I. Hattwick, I. Franco, D. Egloff, E. Frid, V. Lamontagne, TeZ, C. Salter and M.M. Wanderley - Proceedings of SMC, 2015.

  My contribution to this work is the design of a haptic envelope system and a vocabulary of haptic effects to be delivered by a whole-body vibrotactile augmented suit. I contributed, together with the other authors to the design of the suit and to the software development.

- Chapter 6 *"Follow the Tactile Metronome: Vibrotactile Stimulation for Tempo Synchronization in Music Performance"* - M. Giordano and M. M. Wandeley - Proceedings of SMC, 2015.

  My contribution to this work is the conception and design of an experiment aimed at investigating the effectiveness of a tactile metronome system in music performance. I performed acquisition and analysis of the experimental data.

The research conducted in this thesis was approved by McGill University's Research Ethics Board. Ethics certificates number: 48-0613, 193-1013 and 202-1114.

Contents

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List of Acronyms

AC	Alternating Current
DC	Direct Current
DMI	Digital Musical Instrument
DSP	Digital Signal Processing
ERM	Eccentric Rotating Mass
IC	Integrated Circuit
IOI	Inter Onset Interval
ISO	International Organization for Standardization
LRA	Linear Resonant Actuator
OSC	Open Sound Control
PWM	Pulse-Width-Modulation
RMS	Root Mean Square
SD	Standard Deviation
THD	Total Harmonic Distortion

Chapter 1

Introduction

In this thesis we present our work on integrating haptic, and more specifically vibrotactile technology, into interfaces used to convey musical information. Haptics is an umbrella term, which encompasses both tactile and kinesthetic perception: the former describes the perception of properties such as temperature, pressure or texture and is mediated by a network of specialized receptors embedded in the skin; the latter pertains to the perception and awareness of the relative position and orientation of our limbs, as well as to the estimation of the forces applied or exerted by them, and it is issued by receptors in our skin, tendons and joints [Grünwald, 2008].

Haptic devices are devices that incorporate technology specifically designed to address this sensory channel. Examples include: force-feedback devices, such as motorized robotic arms used to provide, for instance, kinaesthetic feedback in tele-operations; and vibrotactile-augmented devices, which stimulate a user's sense of touch by means of mechanically produced vibrations. Since the advent of the "mobile revolution", and the widespread availability of smartphones or tablet computers, the latter class of devices has proliferated, and this type of technology is now inexpensive and readily available.

The development of tactile-augmented interfaces has been fostered, at the same time, by the progress of our understanding of the psychophysical properties of the sense of touch. Since the pioneering studies in the late '50s [Von Békésy, 1959], we have nowadays established a model of the neuro-physiological properties of tactile sensation [Gescheider et al., 2010], and several studies have investigated humans' ability to process information via this sensory channel [Gallace et al., 2007].

Given this context, it is not surprising that haptic technology and haptic interaction design (i.e., the conception, design and evaluation of the interaction between a user and a haptic device) are now ubiquitous terms in both industry and academic institutions. Haptic interfaces are being designed and introduced in the market for applications such as mobile computing, automotive, smart wearables and musical interfaces, and new ways of conveying meaningful information to users via the sense of touch are being constantly developed.

1.1 Goals of this Research

Haptic researchers and interaction designers have been investigating new ways of communicating via a user's sense of touch by means of tactile effects (i.e. specifically designed tactile stimuli) used to provide information such as navigational cues [van Erp et al., 2005], rendering of textures [Kyung and Lee, 2009] or system notifications [Qian et al., 2013]. Systematic studies have been conducted to assess the efficiency of tactile displays in these contexts, and new prototypes and applications are constantly being designed.

In the music domain, the sense of touch can be used to convey relevant musical information, such as articulation Puckette and Settel, 1993 and timing Verrillo, 1992, especially in professional performances Keele, 1973. Several tactile augmented interfaces for music performance and practice have been created in the last two decades (see Chapter 2) but for very few of these a thorough evaluation of their effectiveness has been conducted. In this dissertation we address the question of developing and evaluating meaningful ways of communicate with a user's via the sense of touch in the context of musical interaction.

Our research focuses on the development of a systematic approach to the design and evaluation of tactile effects for musical practice and performance. These effects are delivered by specialized vibrotactile displays: interfaces augmented with one or several vibrating actuators, specifically designed to present either localized or distributed vibrations arranged in patterns.

We propose two main applications: 1) the development of techniques to model and render the vibrational behavior of several vibrating structures, and 2) the design of stand-alone tactile-enabled devices capable of conveying information to assist performers.

Our approach to the design of these interfaces starts from the identification of the most suitable actuator technology for each application, whose choice is dictated by the physical properties of the actuators themselves and the electronics needed to drive them. We provide in context, user-based evaluations of our displays and interactions, with the aim of assessing their effectiveness and guaranteeing transparency of the interface.

Finally, we describe real-world applications of these interfaces, such as concerts and installations in which our devices have been successfully used by professional musicians, composers and the general audience.

1.2 Structure of the Thesis

This dissertation is divided into seven chapters:

In **Chapter 1**, the present chapter, we have presented the context of this work, and laid out its main research goals.

Chapter 2 provides the reader with a brief overview of the most relevant literature on tactile physiology and perception. Moreover, it presents some of the most significant work in the music technology domain, addressing the design of active vibrotactile feedback for musical interaction. This presentation is organized into a taxonomy of tactile feedback comprising three main categories: *tactile notification*, *tactile translation* and *tactile synthesis.* The examples presented for each category also provide an overview of the many actuator technologies available on the market, each of which presents its own advantages and disadvantages for the interface design.

This last aspect is the addressed in **Chapter 3**, which deals with the characterization of vibrating actuators. We present procedures and results we obtained in the analysis of the physical properties of three classes of actuators: voice-coils, eccentric rotating masses and linear resonant actuators. Based on our analysis, we provide guidelines to justify the choice of a particular actuator technology for each one of the three categories of applications presented in the previous chapter. These actuators are then used in real word applications which are described in the following chapters.

In **Chapter 4**, we present results in the context of tactile translation applications using voice-coil actuators: we present frequency compensation techniques and illustrate how these can be used to model and render the vibration of several vibrating structures, in the context of musical interaction. Subsequently, we provide an example of the use of voice-coil actuators to improve the interaction with the haptic model of a bowed string, rendered using a low-end force feedback device, and to render the haptic behavior of a wooden floor onto a mobile platform.

Chapter 5 describes the development of the hardware and software solutions used to control a whole-body tactile-augmented suit for a multi-sensory art installation. We present the communication protocol we implemented to transmit tactile information, as well as the tactile synthesis of a vocabulary of effects. Subsequently, we present our contribution to the development of a language of abstract tactile icons, which represent the building blocks for a wearable score system to be conveyed to musicians by specialized tactile-augmented garments. We provide a first evaluation of these icons in the context of music performance.

Chapter 6 presents the use of ERM motors for the development of tactile notification delivered to performers. These notifications provided on-stage feedback about their interaction with a live-electronics system. We present an application of this system, which we used to deliver tempo information for the performance of a piece composed for a saxophone quartet equipped with tactile notifiers.

Lastly, **Chapter 7** summarizes our results, and presents concluding remarks and future work.

Chapter 2

Background

In this Chapter we present a review of the most relevant literature on the physiology of tactile perception and tactile communication, with focus on musically relevant information. We distinguish between temporal and spatial tactile effects, to emphasize the two complementary, but not mutually exclusive, approaches that can be taken when designing these types of cues.

Subsequently, we present an abstract framework to situate our work in the context of the design of interfaces for musical performance and practice. We provide a description of what Digital Musical Instruments and stand-alone devices are, and describe how these can be augmented via actuators to provide haptic feedback and stimulation. We then provide a review of the literature on haptic augmented tactile interfaces, with particular emphasis on vibrotactile feedback and stimulation. For the latter, our review will be structured in a taxonomy comprised of three categories, which will be used to frame the work presented in the rest of this dissertation.

2.1 Bases of Physiology of the Sense of Touch

Tactile perception operates through a network of cutaneous receptors present in the human skin — 17,000 receptors have been estimated to be present in each hand [Vallbo and Johansson, 1984] — and is responsible of sensations like pressure, temperature, texture, orientation and vibration. Its role is crucial in motor control and in the execution of many simple and complex tasks.

In glabrous skin we can identify three different layers: *epidermis*, *dermis* and *subcutis*;

each of these layers contains different kinds of receptors, of which those responsible for the perception of vibrotactile events are the *Meissner*, *Merkel*, *Pacini* and *Ruffini* corpuscles [Verrillo, 1992]. Each is responsive to very specific features of a stimulus and is associated with a different sensory channel. Two families of corpuscles exist, the Fast Afferent (FA) family and the Slow Afferent (SA) one: the former is characterized by a rapid cessation of the mechanoreceptors' response to a given stimulus, while in the latter, corpuscles keep responding longer after the stimulation has ceased. Meissner and Pacini's corpuscles belong to the FA family, while Merkel and Ruffini's belong to SA family [Verrillo, 1992; Lederman and Klatzky, 2009]:

- Pacini (FA): Pacini's corpuscles are present in the deeper layers of the skin and their primary role is to protect the nerves from the vibrations given by the manipulations of objects in everyday life. They operate as a high pass filter, not allowing the low-frequency, powerful vibrations to reach the nerves. On the other hand they are very sensitive to frequencies higher than $40Hz$ and up to $300Hz$, and they are able to sense vibrations of amplitude smaller than $0.1\mu m$ [Halata and Baumann, 2008]. The way Pacinian receptors behave when firing neural signals after the reception of a stimulus is very similar to the way the auditory system reacts — it has been shown that the Pacinian channel behaves as a critical band filter [Makous et al., 1995]. This seems to be evidence to the fact that the Pacinian channel is the one to be mainly exploited for the mediation of musical vibrotactile events [Birnbaum and Wanderley, 2007].

- Meissner (FA): these receptors are very sensitive to lower frequencies and occupy the superficial part of the dermis. Their spatial resolution is not very high, meaning that they cannot accurately sense where the stimulation is taking place; their principal function is to guide grip control on the objects we manipulate.

- Merkel (SA): These cells have a high spatial resolution and are sensitive to the changes in texture of the objects manipulated.

- Ruffini (SA): The functionality of these cells is the most difficult to identify. Being sensitive to lateral stretching, they could be involved in the control of moving objects or in the determination and self-awareness of the position of body parts, according to the superficial tension of the skin.

2.1.1 General properties of the tactile sensation

Researchers have investigated the properties of the sense of touch, especially in terms of perceptual thresholds and peak sensitivity as a function of the frequency of the stimuli applied to the skin. The hands are probably the body part that has been more thoroughly characterized, and their sensitivity contours have been determined by means of several perceptual studies conducted using pure sine waves and different contact surface sizes [Verrillo, 1992]. The frequency response of the skin has a U-shaped form which spans from $40Hz$ to $1000Hz$ with a peak sensitivity around $250Hz$ (see Fig. 2.1). Equal sensation magnitude curves, analogous to the Fletcher-Munson curves for the auditory sense [Fletcher and Munson, 1933], have also been computed [Verrillo, 1992] (see Fig. 2.2).

Recently, several studies have addressed the issue of determining perceptual thresholds for other parts of the body [Morioka et al., 2008] and for stimuli other than pure tones. The experimental results we mentioned so far apply to glabrous skin; hairy skin is generally characterized by higher threshold and lower peak sensitivity values compared to glabrous skin [Bolanowski et al., 1994; Verrillo, 1966b; Mahns et al., 2006]. Moreover, recent studies suggest that for complex waveforms, sensitivity to tactile sensation could go above the previously stated $1000Hz$ limit [Wyse et al., 2012].

Other phenomena that could affect tactile perception have also been examined, of which we provide a brief, non-exhaustive overview: *Masking*can have a significant impact on the perception of a tactile stimulus: *masking* occurs when the presence of a stimulus makes the primary one go undetected; it is an important factor to consider since it can affect threshold. *Enhancement* works the opposite way as *masking*, by amplifying the perceived magnitude of a stimulus followed by a second one. *Summation* occurs when the second stimulus is integrated with the first one, without changing its perceived magnitude. For a more complete review on the topic see [Verrillo, 1992] and [Birnbaum and Wanderley, 2007]. The concurrent effect of one or more of these phenomena can shape the perception of simple and complex tactile stimuli, and controlling for each of these effects simultaneously can be a very difficult task.

In the remainder of this thesis, we mostly address issues concerning the effects of *Adaptation*. This phenomenon occurs when the extended exposure to a given stimulus decreases the sensitivity to the following ones, also increasing threshold or decreasing

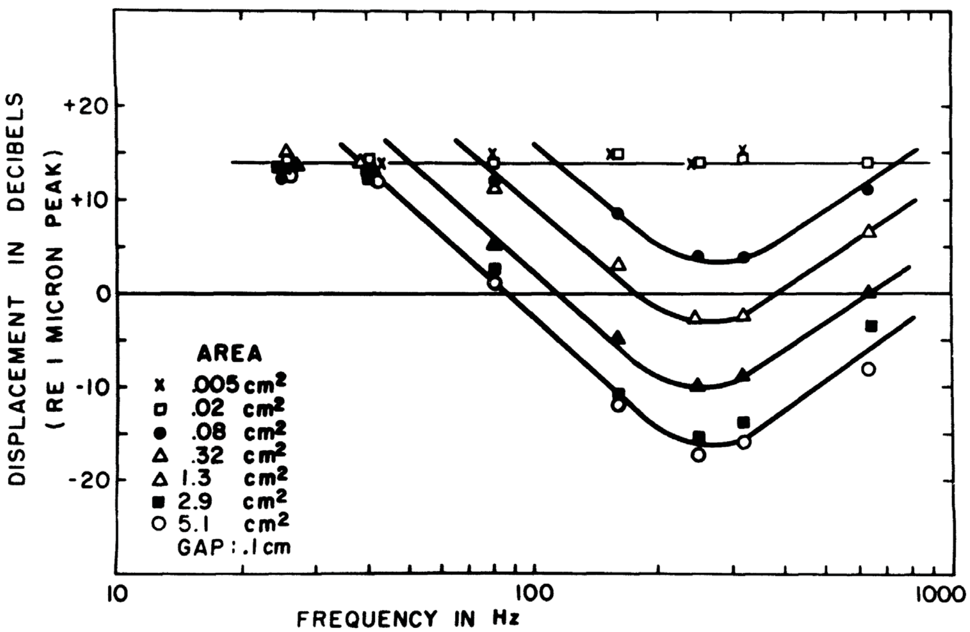


Figure 2.1: Thresholds for vibrotactile sensation, measured on the thenar eminence of the right hand. The curves show the dependency of threshold on sinusoidal frequency and contact size. Figure from Verrillo, Ronald T., "Vibration Sensation in Humans" in Music Perception, Vol. 9, 3, Spring 1992, pp. 281-302 (c) 1992 by the Regents of the University of California. Published by the University of California Press. Used with permission.

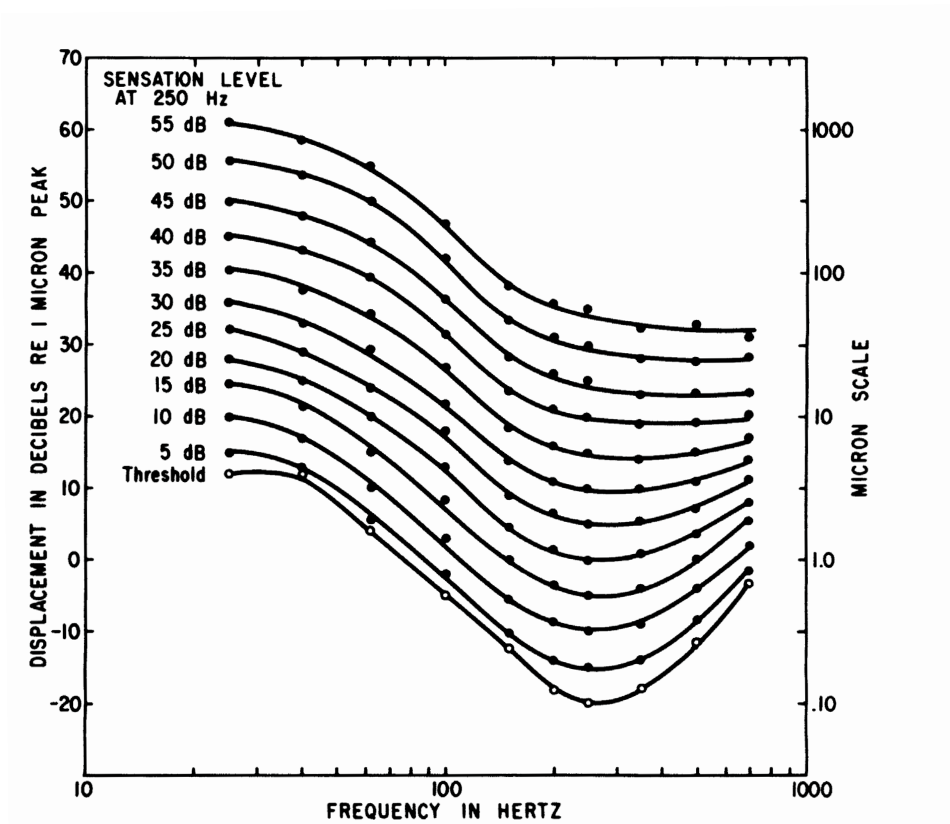


Figure 2.2: Equal sensation magnitude curves for vibrotactile sensation. Figure from Verrillo, Ronald T., "Vibration Sensation in Humans" in Music Perception, Vol. 9, 3, Spring 1992, pp. 281-302 (c) 1992 by the Regents of the University of California. Published by the University of California Press. Used with permission.

their perceived magnitude. Recovery times from adaptation vary according to the stimulated body locus and to the intensity of the leading stimulus Verrillo, 1992. It also been shown that adaptation can improve frequency discrimination Goble and Hollins, 1994.

2.2 Conveying information via the sense of touch

The tactile sense can be used for conveying information both in the temporal and the spatial domain e.g. discrimination of different frequencies and shift of attention on different parts of the body where a tactile stimulus is presented. A combination of factors in both domains can be used to generate more complex tactile stimuli, or to compensate for the lack of flexibility in terms of temporal properties, present in certain types of vibrating actuators (see Chapters 3 and 5).

2.2.1 Temporal domain

2.2.1.1 Amplitude

Researchers have investigated absolute detection threshold and perceived amplitude of tactile stimuli. As mentioned before, it has been shown that Pacinian corpuscles can sense displacements as small as $0.1\mu m$, but many conditions affect the determination of absolute threshold: parameters such as body site [Verrillo, 1966a; Morioka et al., 2008], temperature [Ide et al., 1985], frequency and size of the stimulated area [Verrillo, 1992; Oey and Mellert, 2004] have all been shown to contribute to the detection of tactile stimuli and their perceived magnitude. The dependence on such a high number of factors makes it difficult to establish beforehand if a given stimulus will be supra-threshold.

In terms of the perception of amplitude difference (i.e. the just noticeable difference between two stimuli), the threshold is relative the reference stimulus and is expressed as a Weber fraction [Heller and Schiff, 2013] — i.e., the fractional increase of the new stimulus with respect to the reference — and it has been shown that a difference of 10% to 30% in amplitude is required to guarantee robust discrimination [Israr et al., 2006; Choi and Kuchenbecker, 2013].

2.2.1.2 Pitch

It has been shown that, compared to auditory perception, frequency discrimination performance using solely tactile information is poor [Rothenberg et al., 1977; Verrillo, 1992] and dependent on different factors such as: the amplitude of the vibration [Morley and Rowe, 1990]; the presence of an adapting stimulus, which, if close in frequency to a reference one, can improve the discrimination between other stimuli and the reference [Goble and Hollins, 1994]; the effects of training on a specific part of the body [Harris et al., 2001]. It has also been shown [Rothenberg et al., 1977] that frequency discrimination seems to be more efficient in lower frequency range: between 7 and 10 different frequency steps (according to the part of the body) can be identified up to $90Hz$.

Branje et al., [2010] measured the ability of participants to discriminate vibrotactile frequencies, using large voice-coils placed in contact with their backs; results showed that participants in the study could effectively discriminate frequency separated by 1/3 of an octave. Romagnoli et al., [2011] conducted an experiment in which they asked two groups of Italian and Indian musicians to discriminate between a western and an oriental scale, played on an harmonium. Results showed correct discrimination rates of the ethnic origin of the scale, up to 77% without significant differences between the two groups of participants. The authors hypothesize that bone conduction of the vibrations could have had an important role in the experiment, but they did not have any possibility to evaluate if this was actually the case.

Overall, results from these experiments show that participants are capable of discriminating frequencies by touch, and that this discrimination is often a function of the pitch of reference stimulus [Choi and Kuchenbecker, 2013]. A relative difference, again expressed as a Weber fraction, ranging from 15% to 30% has been indicated [Israr et al., 2006] to be enough to guarantee reliable discrimination.

2.2.1.3 Rhythm

The capacity of tactile sense to perceive rhythmical patterns has not been explored in depth, but some studies suggest that the sense of touch performs well in rhythm recognition tasks. Kosonen and Raisamo, [2006] and Jokiniemi et al., [2008] compared performance of participants in same/different judgments of rhythmical patterns presented unimodally in the auditory, tactile and visual modality. While the auditory modality presented the highest rate of recognition, the tactile modality performed better than the visual one, and close to the auditory. Rhythmical patterns have also been used by Brown, Brewster, et al., [2005] as a parameter for defining distinguishable tactile effects (i.e. tactile icons, or *tactons*): a series of three different rhythms were used to deliver messages about the interaction with a mobile phone. Results showed correct recognition rates of the tactile patterns up to 90%.

2.2.1.4 Waveform and Timbre

Discrimination between different waveforms has also been investigated. Bensmaia and Hollins, [2000] proposed an experiment in which two sinusoidal waveforms combined together were presented to the skin of participants, producing a complex-waveform vibrotactile stimulation. Results showed that participants, when asked if they could identify the presence of two separates components in the signal, performed better on lower frequencies (combination of a $10Hz$ sinusoid with a $30Hz$ one) than higher frequencies (sinusoids at $100Hz$ and $300Hz$) for which the performance was comparatively poor.

Russo et al., [2012] performed a series of experiments to determine the capability of discrimination between musical timbres solely by the sense of touch. Discrimination of tones from cello, piano and trombone, matched for fundamental frequency and amplitude, and delivered through voice coils embedded in a chair, was found to be above chance. These results suggest that complex frequency content of tactile stimuli can effectively be discriminated.

2.2.2 Spatial Domain

2.2.2.1 Acuity, pattern recognition and numerosity

Evaluating the spatial resolution of the tactile sense is an important factor in the design of devices that rely on a user's capability of distinguishing the part of the body to which a tactile stimulus has been applied. Cholewiak and Collins, [2003], in their review of the literature on tactile spatial acuity, concerning *two-point limen* studies (i.e., the investigation of the minimum distance to perceive two stimuli as spatially distinct), remark that the topic has been extensively studied in the last 170 years. Spatial acuity is at the base, for instance, of the understating of the Braille alphabet, for which a particularly elevated resolution at the fingertips must be developed [Cholewiak, Brill, et al., 2004]. These studies though, have mostly taken into account pressure and tapping stimuli[1], while less has been done concerning spatial acuity for vibrotactile stimuli. Cholewiak and colleagues performed a series of experiments to test participants' ability to discriminate locations where a vibrotactile stimulus was presented. Seven points of the forearm, three points on the upper arm, two points on the shoulder [Cholewiak and Collins, 2003] and seven points around the lower torso [Cholewiak, Brill, et al., 2004] were tested. Results showed a comparatively poor performance for what concerns the forearm, with results superior to 70% only in two points, the elbow and the wrist. Better performances were achieved for the torso, for which all the points were identified more than 70% of the times.

Other studies confirm these results; van Erp, [2005] showed that the torso has a spatial acuity of about $3cm$, remarking though how the discrimination is highly dependent on two temporal factors: the duration of the stimuli and the temporal offset between two consecutive stimuli. Piateski and L. Jones, [2005] also confirmed these results: they presented vibrotactile patterns using a tactile display on the forearm and on the lower back. While the recognition rate attained almost 100% for some patterns displayed on the back, statistically significantly worse performances were obtained for the fore-arm. These results suggest that the sense of touch can proficiently be used to give directional information or to give the user specific directives, associated to predetermined patterns. We will present applications that address this issue in Chapter 5.

Gallace et al., [2006] investigated the ability of participants to perform numerosity judgments via the sense of touch. They conducted an experiment in which participants had to identify how many tactile stimuli were presented simultaneously on their body, while wearing a tactile display composed of seven different actuators distributed on arms, legs and torso. Results show that the error rate (defined as the number of wrong responses with respect to the total number of trials) increased to more than 50% when more than two stimuli were presented at the same time. This seems to suggest that

[1] See Fig. 2.3 for an overview of spatial acuity and two-point limen thresholds across the body and [Lederman and Klatzky, 2009] for an exhaustive overview of the topic.

the amount of information that can be processed at the same time is modest, at least if the tactile stimuli are not presented in the form of temporally or spatially organized patterns.

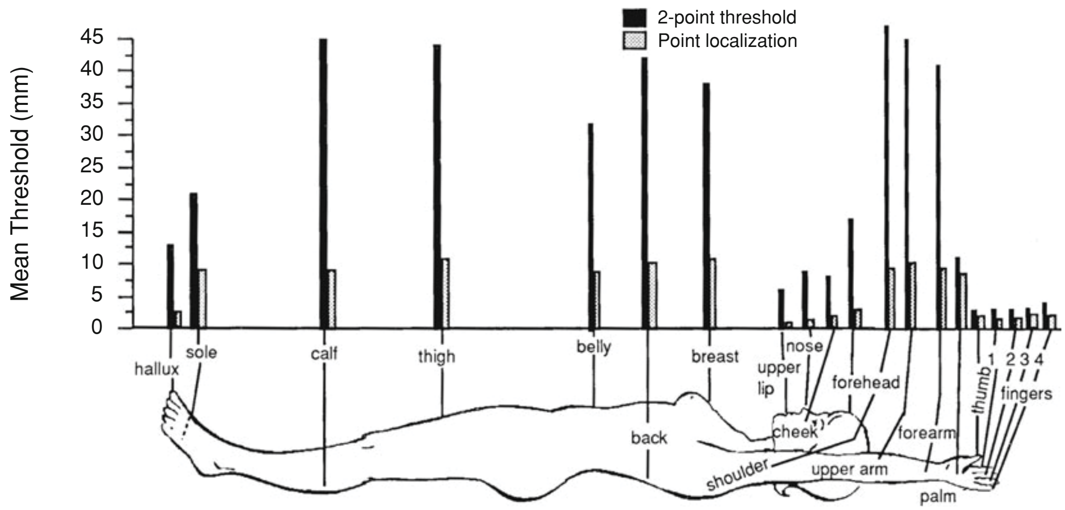


Figure 2.3: Two-point discrimination and point localization threshold over the human body. We can see remarkable differences according to the body part, with hands and fingertips being the most sensitive, back and legs the least sensitive. Figure from *Encyclopedia of Human Biology*, Vol 7, S. J. Lederman, "Skin and Touch", page 55, Copyright Academic Press (1991). Adapted from S. Weinstein, 1968. Used with permission.

2.2.2.2 Tactile illusions

Tactile illusions have been thoroughly investigated in the last decades, since they offer a privileged way to investigate the mechanism underlying tactile perception [Hayward, 2015]. The most known is the so-called "cutaneous rabbit" illusion [Geldard and Sherrick, 1972]. A specific temporal and spatial pattern of stimulation between two points on the skin can give raise to the emergence of the sensation of a moving point that flows between the two stimulated points. This illusion can be used to simulate apparent movement of a point on the skin, and several of the haptic effects we describe in the following Chapters will leverage this illusion to produce the effect of continuous tactile motion.

2.2.2.3 Attention

An extensive review on the subject of tactile attention can be found in Spence and Gallace, [2007]. The authors present evidence showing that after the presentation of a tactile stimulus in a part of the body, subsequent stimuli in the same location, in the tactile or other modalities, can more easily be detected. Tactile stimulation can so be used to direct users' spatial attention, increasing the detection rate of stimuli delivered to other modalities.

2.2.3 Active and Passive Touch

Touch sensation can also be described in terms of active and passive touch. Passive touch is the sensation elicited by *being touched*, while active touch pertains to a user's active exploration by the sense of touch [Gibson, 1962]. While it has been suggested that active touch can provide better experience of the objects and surfaces being touched [Lederman and Klatzky, 1987], it can also detrimental to overall sensitivity by increasing perceptual thresholds [Post et al., 1994].

2.2.4 Discussion

Gallace et al., [2007], commenting on the state-of-the-art of tactile displays, remark that even though *"[t]he suggestion that the body surface might be used as an additional means of presenting information to human-machine operators has been around in the literature for nearly 50 years"*, so far we witness to a *"surprising lack of applied success"* with these kind of solutions. The authors claim that the reason for this lack of success of tacile displays that make use of the whole body surface, is to be found in *"fundamental failure of early research to consider the central/cognitive as well as the peripheral limitations that may constrain tactile information processing across the body surface"*. It is indeed true that most of the literature on the subject of tactile perception we have presented so far is focused on the study of phenomena that take place at a mechanoreceptor level, and for a few selected body parts. Moreover, few of these studies evaluate the properties of the sense of touch in the context of experiments in which participants are engaged in any sort of task.

The work presented in this dissertation addresses some of these issues: testing the design and rendering of tactile effects and interactions on users actively engaged in tasks as demanding as performing on a musical instrument. While we do not aim to evaluate users' performance from a psycho-physical point of view, we want nonetheless to evaluate the effects of cognitive and attentional load on the effectiveness of tactile communication.

To summarize the previous results, we can conclude that tactile stimulation can be used locally to convey information such as pitch, rhythm, timbre and amplitude; a tactile stimulus can also be used to capture user attention and spatially direct it. When more spatially extended tactile displays are used, covering the torso for example, spatial resolution varies in function of the body part, with distal body parts presenting higher acuity. If more complex signals need to be used, including several simultaneous or close temporally-spaced stimuli, they need to be organized in patterns to be fully processed at higher cognitive levels.

2.3 Haptic Technology in Interfaces for Musical Interaction

Haptic technology has been widely used in the development of interfaces for musical expression and musical interaction in general and two main classes of devices can be identified in this context: Digital Musical Instruments and stand-alone interface.

Digital Musical Instrument (DMIs) are a class of instruments which consist of a "gestural controller", capable of sensing users' gestures, and a sound generating unit, usually implemented as a digital synthesizer [Miranda and Wanderley, 2006]. These two independent units are connected by an arbitrary mapping layer [Wanderley and Depalle, 2004], which becomes the core of the instrument design.

Gillespie, [2001], affirms that *"[b]y comparing the instrument's actual sound output against a desired sound output (internally conceptualized), the performer can make comparisons and modify subsequent manipulations of the instrument in order to produce new sounds that more closely match the desired sounds. Alternatively, a musician may compare the mechanical information arriving in the haptic feedback path against a desired haptic response, then modify subsequent manipulations to minimize that difference"*. The tactile and kinaesthetic feedback coming from the resonating parts of the instrument give the performer important information about his/her interaction. It has been shown that the vibrations produced by the instrument can be sensed by musicians [Askenfelt and Jansson, 1992] and that they can shape, for instance, the instrument's perceived quality [Keane and Dodd, 2011; Goebl et al., 2005]. Moreover, this feedback proved to be an essential component in the player-instrument interaction [Marshall and Wanderley, 2006] especially in expert performance [Keele, 1973] and has been stated to be the only component fast enough to control parameters such as articulation [Puckette and Settel, 1993].

In DMIs, the decoupling of gesture acquisition from sound synthesis has the important effect of breaking the mechanical feedback loop between performer and sound producing structures. Haptic feedback becomes then an arbitrary design factor [MacLean, 2000] and the choice of actuators and signals used to drive them define the instrument's architecture.

Haptic-enabled interfaces can be used, at the same time, to provide tactile stimulation and feedback not only if embedded into musical instruments, but also in a stand-alone manner, by means of tactile displays and wearable devices that can be used to go beyond the direct performer-instrument interaction. In the context of music performance, these devices, for instance, can convey information about performers' interaction with a live-electronics system [Michailidis and Berweck, 2011], or as learning tools to direct and guide users gestures via vibrotactile feedback [van der Linden et al., 2011]. They can also be used to convey score cues to an on-stage performer [M. Schumacher et al., 2013], by means of abstract languages of tactile icons [MacLean and Enriquez, 2003].

These displays usually provide either localized (i.e. single body site) or distributed vibrations (via actuators placed on multiple body sites), requiring the design of tactile effects more centered on temporal or spatial properties respectively, or on a combination of both.

2.3.1 Models of Haptic-Augmented Interfaces

The relationship between performer, haptic-augmented musical interface (either stand-alone device or DMI) and audience can be complex and a number of abstract models of the interaction between these components can be found in the literature.

In the case of DMIs several models exist, each of which emphasizes different as-

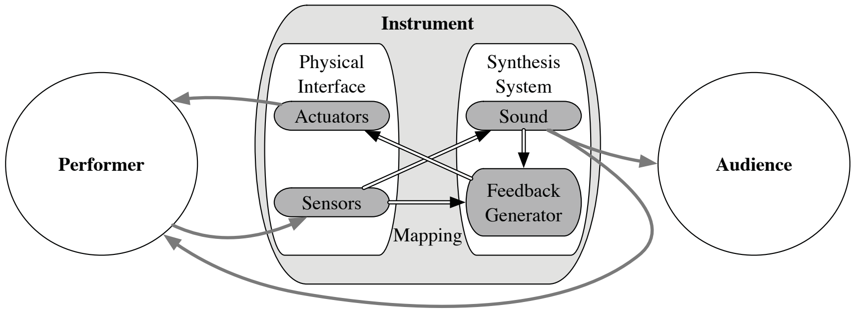


Figure 2.4: A model of a Digital Musical Instrument as proposed by Marshall [Marshall, 2008]. The haptic feedback is synthesized in a "feedback generator".

pects of the instrument's design. Marshall, [2008] reviews four of these models — respectively by Wanderley and Depalle, [2004], Bongers, [2000], Cook, [2004] and Birnbaum and Wanderley, [2007] — and proposes a hybrid model merging characteristics from the previous four. This can be seen Fig. 2.4: a physical interface comprised of sensors and actuators is mapped to a digital synthesizer and a feedback generator. These are responsible of the production of sound and haptic feedback, with the latter being generated by either sensor data or sound. In Fig. 2.5 we present an extension of this model, which will act as a framework for the results described in the remainder of this dissertation. Our model is a general representation of the interaction with either haptic-enabled DMIs or stand-alone devices. While the former can provide the performer with both kinaesthetic or tactile feedback, the latter are usually implemented as vibrotactile displays, for reasons that are mainly to be found in current technology limitations: to quote MacLean, [2008], *"displays must be miniature, portable, and low power, and currently, this is harder to achieve when displaying forces"*. Rare examples exist though of stand-alone kinaesthetic interfaces in the field of haptic guidance [Grindlay, 2008; Nakagaki et al., 2015] (i.e. actively directing users movement by means of motorized exoskeleton-like interfaces).

Another important aspect of our model is the substitution of the *feedback generator* by a *haptic generator*. The term feedback indicates the reaction of systems to a user's direct action. In the case of the interaction with a traditional musical instrument for instance, the acoustic and haptic feedback provided to the musician are tightly coupled, since they are issued from the same physical process, i.e. the resonance of the body of the instrument itself. In the context of haptic augmented interfaces, the haptic channel

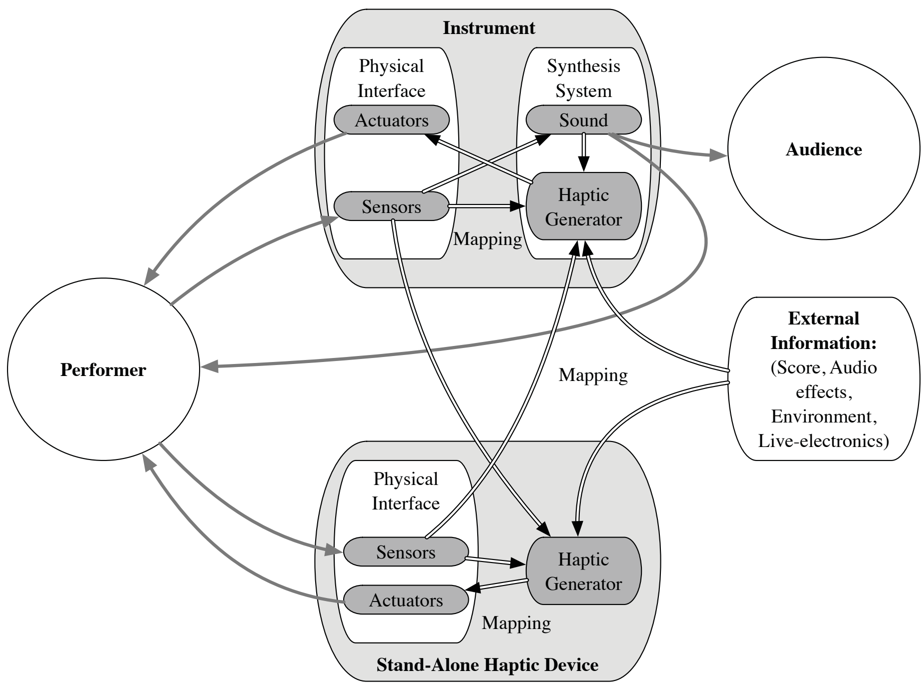


Figure 2.5: Model of a DMI and Stand-Alone Haptic Device. In both devices, a Haptic Generator is used to produce haptic feedback and stimulation, which is issued from mapping of sensor data or external information. The simultaneous use of both types of devices is also possible, and sensor data from either device could be mapped to the haptic generator of the other.

does not need to be limited to the display of feedback, issued as a direct response to performers' actions, but can be mapped arbitrarily to convey information from external sources, such as environmental variables, or score parameters. This is represented by the *external information* source in our model, and in the following Chapters, we will talk about *vibrotactile feedback and stimulation*, emphasizing the dual nature of the information transmitted via the tactile channel, specifically through vibration, and present several applications in both contexts.

2.4 Existing Haptic-Augmented Interfaces

We will now provide a review of the existing literature in the field of the design of haptic-augmented interfaces for musical interaction. We will present examples of both DMIs and stand-alone devices and structure our presentation in terms of the type of feedback or stimulation they provide. We will distinguish between interfaces addressing either the kinaesthetic or the tactile sense, in an *active* or a *passive* way [Bongers, 2000]: passive feedback and stimulation come from the inherent physical properties of the interface and are not issued by the system's haptic generator; active interfaces implement an haptic generator to provide user with the designed kinaesthetic and tactile effects.

For the *active tactile* case, which is the focus of this dissertation, we will provide a three-fold categorization of the results found in the literature, specifically in the case of vibrotactile feedback and stimulation. This taxonomy will be used to frame the work described in the following Chapters.

2.4.1 Passive kinaesthetic feedback

Passive kinaesthetic feedback and stimulation are inherent to the physical characteristics of the controller, and do not require any externally synthesized signal.

O'Modhrain and Essl developed three DMIs that implement passive kinaesthetic feedback. "The Pebble Box" and the "Crumble Bag" [O'Modhrain and Essl, 2004] were used to control an event based granular synthesizer: the Pebble Box consists of a box filled with different-sized pebble stones and a microphone that picks up the noises of the collisions of the pebbles. The kinaesthetic feedback of the interface comes from the physical properties of the pebbles themselves, and the impact sounds act as triggering events on the granular synthesizer. The Crumble Bag follows the same patter and it is aimed to take advantage of natural "grabbing gestures". A fabric bag is filled with different materials that provide haptic feedback and a small microphone in the bag provides the necessary granification triggers to the algorithm. "The Scrubber" [Essl and O'Modhrain, 2005] also implemented the same approach: an eraser embedded with an FSR and two microphones were used to control the synthesis of friction sounds, synthesized by means of granular or wave-table synthesis. The haptic feedback again was directly issued by the manipulation of the device dragged along a surface.

Another device implementing passive kinaesthetic solutions is the Meta-Instrument by de Laubier, [1998], *"a musician-machine interface and a gesture transducer intended for electro-acoustic music, multimedia work, and, more generally, for controlling algorithms in real time"*. The controller has the form of an exoskeleton embedded with buttons that the performer uses to trigger samples and events in the sound, and sensors in the arms used to capture his/her gestures which are mapped to various effects. The latest implementation of the meta-instrument [de Laubier and Goudard, 2006] also implements different solutions of passive kinaesthetic feedback : springs and small pistons connected in the joint of the arm provide a resistive and friction-like sensation to the performer.

Other devices have been designed that take advantage of haptic properties of the controller. An example is the "The GyroTyre" [Sinyor and Wanderley, 2005], a hand-held controller based on a spinning wheel. The kinaesthetic feedback derives directly from the dynamics of the system, and the mapping and synthesis algorithm are designed to take advantage of the haptic feedback. The interface can be used for different musical applications, such as driving a sequencer or continuously modifying effects' parameters.

2.4.2 Active Kinaesthetic Interfaces

Active kinaesthetic feedback is the response of the controller to the user's actions, usually by means of synthesized signals supplied into motors or actuators, which stimulate his/her kinaesthetic receptors. This is most commonly referred to as force-feedback. In active kinaesthetic stimulation, a user's motion is directed by the device's motors, independently from the user's input.

2.4.2.1 Keyboard-like Interfaces

The earliest example of a force-feedback device, specifically developed for musical applications is probably the *Transducteur Gestuel Rétroactif* (TGR) developed at ACROE, France. Its first incarnation dates back to 1978 when [Florens, 1978] developed a *"force feedback stick that could be manipulated in one dimension"* [Miranda and Wanderley, 2006]. These devices evolved in the following years to become a modular feedback device; each of the TGR sticks became an independent "slice-motor", of the exact size of a piano key, whose shape allowed to have multiple keys to be put side by side forming a modular feedback keyboard [Cadoz et al., 1990]. Each key senses position and outputs forces, and the keyboard can be "covered" with different adapters designed for specifically sense and provide feedback to different gestures (a 2, 3 and 6 DOF joysticks are currently produced). The ERGOS system can also be used in the simulation of a bowing interaction, i.e. the simulation of the friction-based interaction between a virtual bow and a virtual string, using a specifically designed bowing adapter for the feedback keyboard [Florens, 2004].

Other examples of force feedback keyboards are the *Touch Back keyboard* by Gillespie, [1992] and the *Multi-Instrument active KEYboard* by Oboe and De Poli, [2002]. These keyboards make both use of voice-coil motors found in recycled hard drives. Both have been used to simulate the haptic behavior of several keyboard instruments. Another attempt to mimic the haptic behavior of a keyboard instrument is the design of an haptic carillon [Havryliv et al., 2009].

2.4.2.2 Bowing Interfaces

The oldest example of a force-feedback device to simulate a bowing interaction was implemented by O'Modhrain, [2001]. The author used the *Moose* interface to control a virtual bowed string. The *Moose*, developed by O'Modhrain and Gillespie, [1997], consists of a plastic puck that the user can manipulate. The puck is attached to flexible metal bars, connected to linear motors, and can be moved in a 2D-space. Two encoders sense the movements of the puck and the motors provide the correspondent force feedback. The device was used in a bowing test, using a virtual string programmed in Synthesis ToolKit (STK) [Cook and Scavone, 1999], where the presence of friction between the bow and the string was simulated using the haptic device. The results showed that the interface was not capable of reproducing a real-world friction well enough to be proficiently used by the players, but still they preferred the haptic-augmented model, despite its unfaithfulness, to the condition without haptic feedback.

The vBow by Nichols, [2002] is a violin-like controller that uses a series of servo-motors and encoders to sense the movement of a rod, acting as the bow, connected to a metallic cable. In its last incarnation, the vBow is capable of sensing moment in 4DOF and producing haptic feedback accordingly.

In Chapter 4 we will present an application of the use of vibrotactile feedback to enhance a force-feedback device to simulate bowing interaction.

2.4.2.3 Generic Controllers

Some controllers using active kinaesthetic technologies have been built that are not inspired by any existing musical instrument. “The Plank” by Verplank et al., [2002] uses recycled hard disk motors to present opposite forces to a user manipulating a sliding flat surface attached on the motors themselves. The device was used by the authors to control sound waves in live performances. Verplank also built the “FORCE-STICK” [Verplank, 2005] , a stick embedded with an FSR sensor attached to the shaft of a motor, capable of sensing the pressure the user applies on the stick and responding accordingly with radial forces. The stick was used as a learning tool for users to explore haptic effects embedded in a synthesis and composition environment. Another generic controller is the “D’GROVE” by Beamish et al., [2003], a turntable-like interface composed by a vinyl disk mounted on a rotating motor. Various effects can be achieved to enhance the DJing experience (different velocities of the disc, haptic cues matching the beats in the track) that are controlled by the user using two sliders.

2.4.3 Passive Tactile Interfaces

Passive tactile is a form of primary feedback, which leverages the use of different types of materials to be used in a controller for musical expression. The properties of these materials (e.g. stiffness, flexibility), can affect the ergonomics of the instrument and its feel in the user’s hands.

The aforementioned Meta-Instrument [de Laubier and Goudard, 2006] for example provides a layer of foam on the keys, providing the user with immediate feedback about the level of pressure he/she is applying.

2.4.4 Active Tactile Feedback and Stimulation: A Taxonomy for Musical Interaction

Rovan and Hayward, [2000] proposed a classification of signals for generating active tactile feedback. In their VR/TX environment for synthesizing tactile feedback for open air controllers, they distinguish between time dependent and space dependent signals. Time dependent signals are used to give feedback on specific events that take place during the interaction, while space dependent signals are used to notify the performer about more complex interactions, such as the continuous variation of an effect according to movement. Their synthesizer was interfaced with custom made actuators, consisting of an unobtrusive vibrating ring and a vibrating platform where the performer could stand.

We propose a similar schematization, identifying in active tactile feedback and stimulation three different categories according to the function that the tactile effects have in the interface design : *tactile notification*, *tactile translation* and *tactile synthesis*.

2.4.4.1 Tactile Notification

The most straightforward application of tactile stimulation is intended for notifying the user about events taking place in the surrounding environment or about results of their interaction with a system. The effects designed for this kind of applications can be as simple as single, supra-threshold stimuli aimed at directing users' attention, but they can also be more complex, implementing temporal envelopes and/or spatial patterns in the vibrations. We find in the literature examples of both simple and complex notifications, and several results in this context will be presented in Chapter 6.

Michailidis and Berweck, [2011] and Michailidis and Bullock, [2011] have explored solutions to provide haptic feedback in live-electronics performance. The authors developed the *Tactile Feedback Tool*, a stand-alone interface using small vibrating motors embedded in a glove. The interface gave musicians information about the successful triggering of effects in a live-electronics performance, using an augmented trumpet or a foot-pedal switch. This device leverages the capacity of the tactile sense to attract a users' attention, while not requiring them to lose focus on other modalities, which would have been the case with the use of on-stage visual displays.

van der Linden et al., [2011] implemented a whole-body stand-alone vibrotactile device. The authors used a motion capture system and a suit, embedded with vibrating motors distributed over the body to enhance violin bowing learning process of novice violin players. A set of ideal bowing trajectories was computed using the motion capture system; when practicing, the players' postures would be compared in real-time with the pre-defined ideal trajectories. If the distance between any two corresponding points in the two trajectories exceeded the threshold value, the motor spatially closer to that point would vibrate, notifying the user to correct his posture. The authors conducted a study in which several players used the suit during their violin lessons.

A similar solution was developed by Grosshauser and Hermann, [2009], which used a vibrating actuator embedded in a violin bow to correct hand posture. Using accelerometers and gyroscopes, the position of the bow could be compared in real-time to a given trajectory, and the tactile feedback would automatically activate to notify the user about his/her wrong posture.

Another application of tactile notifications is the Audio-Haptic Navigation Environment [Niinimäki and Tahiroglu, 2012]: an environment is populated with invisible musical objects, which can either play sound or produce real time effects when activated. The environment can be explored by means of a vibrotactile-augmented glove and a motion capture device. The glove produces haptic feedback when the hand of a user touches the virtual object, providing different notifications according to the type of object (sound producing or effect).

2.4.4.2 Tactile Translation

With tactile translation we refer to two separate classes of applications: one class implements sensory substitution techniques, to convey to the sense of touch stimuli which would normally be addressed to other modalities; the other class describes rendering, via tactile-augmented interfaces, of the haptic behavior of other structures, whose vibrational properties have previously been characterized. Applications of tactile translation techniques will be presented in Chapter 4.

Sensory substitution The field of sensory substitution has been thoroughly investigated since the beginning of the last century. In the early '30s, von Békésy, started investigating the physiology behind tactile perception by drawing a parallel between the tactile and the auditory channel in terms of the mechanism governing the two perception mechanisms [Von Békésy, 1959]. A few decades later, Bach-y-Rita's work was devoted to sensory substitution and brain plasticity [Bach-y-Rita and Kercel, 2003]. The author developed multiple interfaces to, for instance, take advantage of the sense of touch to replace vision in blind people (a device capable of such substitution is called a *Tactile vision substitution system*) [Bach-y-Rita, 2006]. A thorough review of sensory substitution applications can be found in Visell, [2009].

In a musical context, several interfaces have been produced with the aim of translating sound into perceivable vibrations delivered via vibrotactile displays. *Cross-modal mapping* techniques can be utilized to perform the translation, identifying sound descriptors to be mapped to properties of the synthesized tactile translation.

Birnbaum and Wanderley, [2007] developed one of the first examples of tactile translation in a purely musical-related domain. A flute-like controller for breakbeat loops, the BreakFlute, was augmented with small voice-coils placed beneath the keyholes. A tactile translation environment called FA/SA performed the translation of the sound output into tactile stimuli played by the voice-coils, with the aim of recreating a feedback loop between sound output and haptics in a DMI. Performers informally reported a greater degree of "control" while interacting with the augmented instrument.

Karam, Russo, and Fels, [2009] developed a stand-alone interface in the form of an augmented chair (the "Emoti-chair") embedded with an array of eight speakers disposed on along the back. The authors' aim was to create a display for deaf people to enjoy music through vibrations. Following the "Model Human-Cochlea" [Karam, Russo, Branje, et al., 2008], a model of physical translation of the cochlear critical band filter on the back, the authors mapped different frequency bands of a musical track, rescaled to fit into the frequency range of sensitivity of the skin, to each of the speakers on the chair.

Merchel et al., [2010] developed a tactile translation system that they used to build a prototype mixer to be used by sound recording technicians. A mixer augmented with a voice-coil actuator would allow the user to recognize the instrument playing in the selected track only by means of tactile stimulation: a tactile preview mode would be enabled on the mixer, performing a real time translation of the incoming audio. Preliminary results show that users were able to recognize different instruments only via the sense of touch; better performance were obtained for instruments producing very low-frequency vibrations (bass) or strong rhythmical patterns (drums).

Tactile Rendering In tactile rendering applications, the vibrational behavior of a vibrating structure is characterized and modeled so to be able to reproduce it onto a another interface.

A DMI featuring tactile translation capabilities is the Viblotar by Marshall and Wanderley, [2011]. The instrument is composed of a wooden box, augmented with sensors and embedded speakers. The sound output from the instrument can be redirected to external speakers, hence allowing the embedded one to be used for generating additional vibrotactile feedback: the body of the Viblotar can be made vibrate like the body of several acoustical instruments, which has been previously characterized.

2.4.4.3 Tactile Synthesis

Tactile synthesis is the attempt to create compositional languages solely addressed to the sense of touch, in which tactile effects are not just simple notifications, issued from the interaction with a system, but can be units or icons for abstract communication mediated by the skin.

An early example of tactile synthesis is the "vibratese", proposed by Geldard, [1960], who aimed at creating a complete new form of tactile language delivered by voice-coil actuators. Parameters for defining building blocks for the language would be elements such as frequency, intensity and waveform. A total of 45 unit block representing numbers and letters of the English alphabet were produced, allowing for expert users to read at rates up to 60 words per minute.

More recently, much research on tactile synthesis has been directed towards the development of languages of tactile icons, to be delivered via portable interfaces such as mobile phones. Brewster and Brown, [2004] introduced the notion of *tactons*, i.e. tactile icons to be used to convey non-visual information by means of abstract or meaningful associations, which have been used to convey information about interaction with mobile phones [Brown and Kaaresoja, 2006]. Enriquez and MacLean, [2008] studied the learnability of haptic icons delivered to the fingertips by means of voice-coil like actuators. Modulating frequency, amplitude and rhythm of the vibration they produced a set of 20 icons, which were tested in a user-based study organized in two sessions, two-weeks apart. Participants recognition rates reached 80% in the first session after 10 minutes of familiarization with the system, and more than 90% during the second session.

In a musical context, attempts to create compositional languages for the sense of touch can be found in the literature. Gunther, [2001] developed the "Skinscape" system, a tactile compositional language whose building blocks varied in frequency, intensity, envelope, spectral content of vibrations and spatial position on the body of the user. The language was at the base of the *Cutaneous Grooves* project by Gunther and O'Modhrain, [2003], in which it was used to compose a musical piece to be accompanied by vibrations delivered by a custom-built set of suits embedded with loudspeaker-like and piezoelectric actuators.

In terms of tactons, we are not aware of any study evaluating their effectiveness in the context of music performance and practice. This will be objects of the work described in Chapter 5, where we propose a methodology to design and test tactile icons for expert musicians.

2.5 Conclusions

In this Chapter we provided a literature review of the properties of tactile perception by emphasizing the type of information that can be delivered via the sense of touch, either temporally or spatially. In the following Chapters we will provide examples of tactile displays and interactions we have designed, leveraging the experimental results presented in this Chapter.

Subsequently, we provided a literature review of the applications of haptic technology to the domain of musical interaction, in the case of DMIs and stand-alone interfaces. We presented an abstract model of these classes of devices, emphasizing how a *haptic generator* can be used to either provide feedback or stimulation to a user.

In the last Section we presented a review of the literature providing several examples of haptic-augmented instruments. We identified two forms of feedback and stimulation: kinaesthetic and tactile, and distinguished between passive and active interfaces. For active tactile feedback and stimulation, which represent the core of the research presented in this work, we provided a three-fold taxonomy, which we use to categorize the work presented in the literature. For the three categories presented we provide examples of DMIs or stand-alone interfaces implementing active tactile feedback for musical interaction.

The applications presented in our taxonomy convey tactile effects to the user by means of different types of vibrating actuators. These will be the object of the next Chapter, in which we will provide methods to characterize the behavior of these actuators to determine which actuator technology is better suited for each one of the proposed applications.

Chapter 3

Vibrating Actuators - Characterization and Choice

As mentioned in the previous Chapter, several actuator technologies are found in the literature in the implementation of tactile-augmented interfaces. The choice of the desired actuator type is crucial in the device's architecture. Simpler actuators, such as unbalanced masses or solenoids for instance, have the advantage of requiring low power and can be driven by very simple signals such as Pulse-Width Modulation (PWM) [Marshall, 2008]. Loudspeaker-like actuators usually require proper amplification (i.e. suitable for an audio signal), which requires in turn a proper power source, but on the other hand they can provide independent control of amplitude and frequency of vibrations [Marshall, 2008].

In this Chapter we provide a brief summary of the main types of actuators available on the market, with a list of their salient properties. We then present methods to physically characterize their mechanical behavior looking at the effect of both actuator type and driving circuitry.

3.1 Actuators

Many kinds of vibrating actuators exist on the market, which are readily available to be integrated into tactile-augmented devices. A general, thorough review on available tactile-displays and actuators can be found in [Choi and Kuchenbecker, 2013], while an analysis of the most popular actuators used in DMIs and tactile displays for music and media can be found in Marshall, [2008]. Here, we provide a non-exhaustive list of the most widely used actuators, focusing in particular on popular choices for music technology and media applications.

3.1.1 Eccentric Rotating Mass (ERM) Motors

ERM actuators are rotating motors driven by a DC signal, to which an external, unbalanced mass has been attached. When voltage or a Pulse-Width-Modulation (PWM) signal is applied to the motor, it produces vibrations whose frequency content and amplitude are functions of the speed of rotation, which is in turn controlled by the dutycycle of the PWM signal. This means that in ERM motors, amplitude and frequency are coupled and cannot be independently controlled.

3.1.2 Linear Resonant Actuators (LRA)

LRA are small form-factor actuators, whose design can loosely be described as that of a small loudspeaker mechanically tuned to vibrate at predefined resonant frequencies (Fig. 3.9). These actuators can be driven using an AC signal coming from a driver integrated circuit (IC), and can provide sharper reaction times and less power consumption compared to ERM actuators.

3.1.3 Voice Coils

Voice-coil actuators are loudspeaker-like devices which can be controlled using an audio signal. They exist in very different form factors[1] which allows them to be flexibly used in several contexts (small voice coils can be effectively embedded into tactile-augmented tablets for instance, while larger actuators — commonly referred to as shakers — can be used in multi-media applications such as actuated floors and cinema chairs). These actuators provide an independent control of frequency and amplitude of vibration.

[1] A catalog of a popular retailer can be found at [Parts-Express, n.d.]

3.1.4 Piezoelectric Actuators

Piezoelectric actuators are vibrating elements composed of piezoelectric materials, i.e. materials that vibrate when excited through an electric current. These actuators are often used as sound-producing elements in buzzers, but also to generate high-frequency content in loudspeakers. In recent years, high-end mobile devices have started integrating piezoelectric actuators to achieve higher quality haptic effects. These new piezoelectric elements come in the form of thin, adhesive patches that can be easily integrated in the structure of a tablet of a smartphone. They can allow for independent control of frequency and amplitude, but usually require high voltages to operate at the desired intensity range.

3.1.5 Solenoids

Solenoids are mechanical transducers that convert electric energy into linear motion. These simple actuators can be used to generate vibrations by applying an AC signal to them, which causes the moving element to oscillate.

3.2 Physical Characterization

When designing tactile effects to be used in tactile-augmented interfaces, designers need to aim at producing an interface which is ultimately transparent to the final user [Lawrence, 1993]. The term transparency has its origin in the field of teleoperations, in which it refers to the property of a robotic apparatus to allow a seamless interaction between an object and a remote user. In the context of haptic interaction design [MacLean, 2008], a transparent interface permits communication of tactile icons without hindering a user's ability to focus on other tasks, by minimally impacting his/her cognitive load.

To achieve transparency, and design tactile effects readily discernible by the final user, it is important to know beforehand the physical characteristics of the hardware used to produce haptic effects. These characteristics are inherent to the devices and their mechanical properties and can affect the final rendering of the designed tactile effects. In this Section we will provide a list of the most important aspects to consider when characterizing vibrating actuators, together with suggested techniques to achieve this characterization. Subsequently, we provide examples of characterization of three types of actuators, two of which we have extensively used in the remaining part of this thesis.

3.2.1 Amplitude Response

Amplitude response can be defined as a measure of the absolute amplitude of vibration produced by the actuator when varying its control signal over the whole input range. While the input signal varies according to the actuator type, output vibration amplitude can be measured as the mechanical displacement of the moving element of the actuator itself, or of its external enclosure. This can be achieved by means of acceleration, velocity or displacement measures, using tools such as accelerometers, laser vibrometers or high-speed cameras.

In the case of loudspeaker-like actuators, the amplitude response can provide information about how the device reacts to input signals at different signal levels. For instance, given an input sinusoidal signal at a given frequency with linearly increasing amplitude, a flat amplitude response would imply an equally linearly increasing amplitude in the measured output. In the case of another type of actuator, a relation has to first be established between the control signal and the output amplitude. This relation is often complex and can depend on multiple control parameters at the same time. A simple case is that of an ERM motor, in which the only available control parameter is the dutycycle of the PWM control signal. This parameter can be considered as an indirect control over the motor's vibration amplitude and, as we will see, a relation can be established between these two quantities.

3.2.2 Frequency Response and Frequency Content

The frequency spectrum of the vibration produced by an actuator can also be characterized, for instance, by means of acceleration measurements as a function of the input signal.

When characterizing simpler actuators, such as ERMs, we prefer referring to the frequency content of the device's output. When using loudspeaker-like actuators, a frequency response curve can be computed which describes the effect of the actuator on the input signal and describes its behavior as that of a filter. The signals used to drive the chosen actuators should be then equalized [Birnbaum and Wanderley, 2007] to compensate for the response of the actuator itself, together with the response of the circuitry needed to drive it (i.e. power amplifiers), and the enclosing structure.

These factors, combined with the perceptual properties of the sense of touch, have to be taken into account if a perceptually flat frequency response of the system needs to be achieved [Marshall, 2008]. In the design phase, the choice of materials with a linear mechanical response should be preferred to simplify the compensation process.

3.3 Characterization Procedures

Several techniques can be used to characterize the vibrating behavior of an actuator or of a tactile-augmented device. In this Section we will present measurements we performed with the aim of investigating the behavior of several motors of different types, namely ERMs, LRAs and voice-coils, combined with different types of driving units. The main points of our investigation are[2]:

1. ERMs: Amplitude and frequency output; spin-down times. Effect of different driving ICs.

2. LRAs: Amplitude and frequency output; spin-down times.

3. Voice-coils: Frequency response analysis using sinesweeps. Effect of different power amplifiers.

3.3.1 ERMs

The ERMs we used for our investigation are the VPM2 flat rotating eccentric masses from Solarbotics Ltd.[3]. These motors have been used extensively in the remainder of

[2] The measurements presented are a subset of all the possible measurements that could be conducted to characterize vibrating actuators. Our investigation was conducted in the context of several projects, which are described in the following Chapters. We hence limited our scope to the properties relevant in each of the presented applications.

[3] https://solarbotics.com/download.php?file=159e

this work and have been chosen for their cost and ready availability. They have a flat, round form factor (see Fig. 3.1), which allows them to be easily embedded in enclosures and wearable devices. They can be driven using a simple PWM signal, and have only one control parameter: the duty-cycle of the PWM signal. This parameter can be effectively considered as a direct control over the amplitude of vibration.

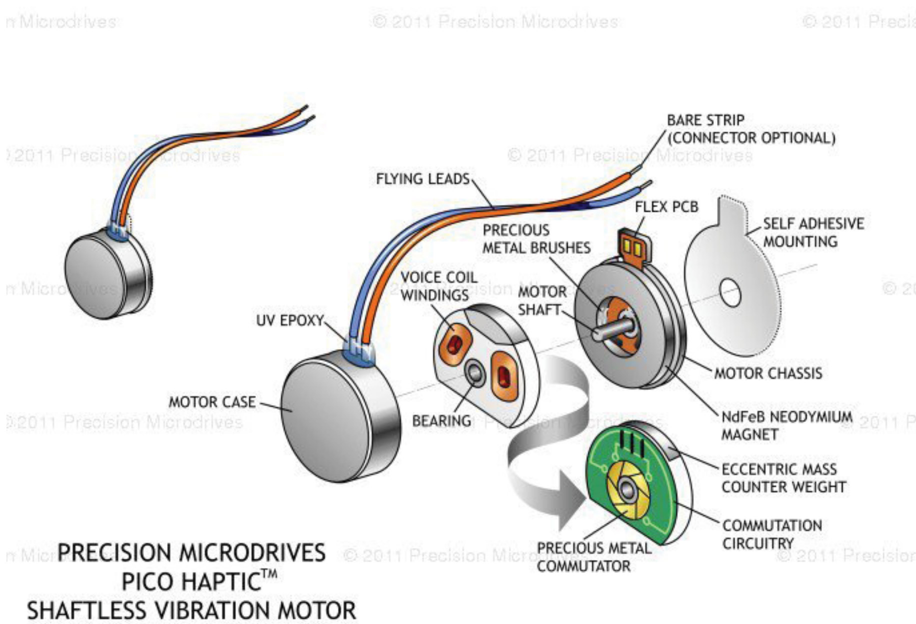


Figure 3.1: Internal schematics of an ERM motor from Precision Microdrives™, similar to the one from Solaribotics Ltd. used for our tests (used with permission).

We compared two different motor drivers in several conditions: a ULN2803A[4] and a LB1837M[5]. The ULN2803A is a simple IC unit which can be used to amplify an incoming PWM signal and supply a steady voltage to several motors thanks to an external power supply. The LB1837M is a low-voltage, bidirectional motor driver unit, which implements a braking functionality capable of reducing spin-down times.

We measured the vibration output of the motor using the ULN2803A and the LB1837M and compared the results of both these drivers, when controlling the VPM2 directly by sending a PWM signal with adjustable dutycycle.

[4] http://pdf.datasheetcatalog.com/datasheet/SGSThomsonMicroelectronics/mXssxrt.pdf

[5] http://www.onsemi.com/pub_link/Collateral/LB1837M-D.PDF

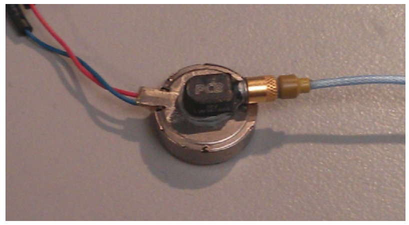


Figure 3.2: PCB 352C23 1-axis accelerometer fixed to the actuator.

3.3.1.1 Amplitude and Frequency Content

We fixed a PCB 352C23[6] 1-axis accelerometer on the top face of the actuator using a small piece of adhesive petro-wax (see Fig. 3.2) and measured the actuator-produced vibrations for ten discrete PWM dutycycle values (10% to 100%) to assess the actual amplitude of vibration and average peak frequency at each step. We performed these tests driving the actuator via the ULN2803A and the LB1837M IC units respectively, both connected to an Arduino[7] board which generated the PWM signal.

Figures 3.3 and 3.4 show the vibration RMS amplitude and mean frequency content for both IC units, while Fig. 3.5 shows the normalized frequency content for the two ICs at two dutycycles. The vibration output was recorded for three seconds and a bandpass filter was applied between 40Hz and 1200Hz (a range that covers the most relevant bandwidth for tactile stimulation [Verrillo, 1992]). For the RMS acceleration amplitude, expressed in dB, the reference value was set at 10^{-6} m/s^2 as per ISO standard R 1683.

These measurements show a similar behavior between the two ICs for what concerns the RMS amplitude. In terms of frequency content, as shown in Fig. 3.5, a more prominent peak is visible at $150Hz$ in the four conditions, with the LB1837M driver displaying a noisier behavior especially for the 40% dutycycle. This is visible in the mean frequency content plot in Fig. 3.4, in which for the 40% dutycycle the ULN2803A differs from the other driver of almost 200 Hz. The difference in mean frequency content is less pronounced for higher dutycycles. This difference can play a role in the perception of the motor's amplitude of vibration, since, as shown in Fig. 2.2, perceived vibration amplitude is directly linked to frequency.

[6] `http://www.pcb.com/Products.aspx?m=352C23`
[7] `http://www.arduino.cc`

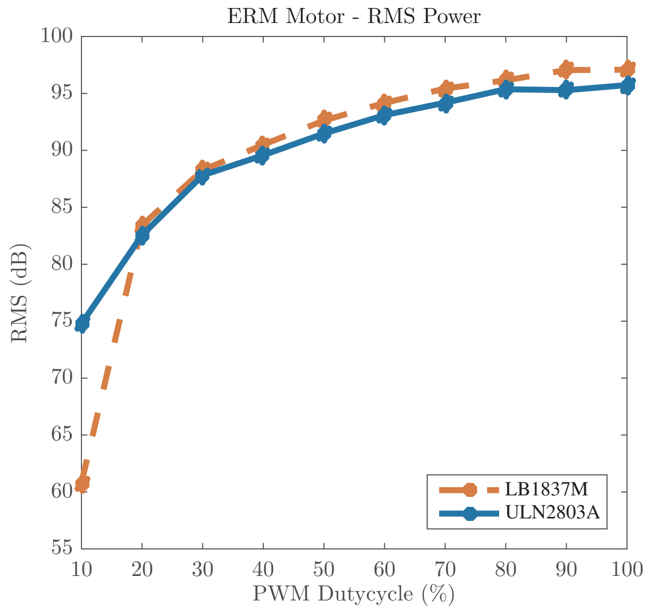


Figure 3.3: The RMS amplitude of vibration (in dB) as a function of the PWM dutycyle. The overall vibration output is comparable for the two IC drivers, with the exception of the 10% dutycycle.

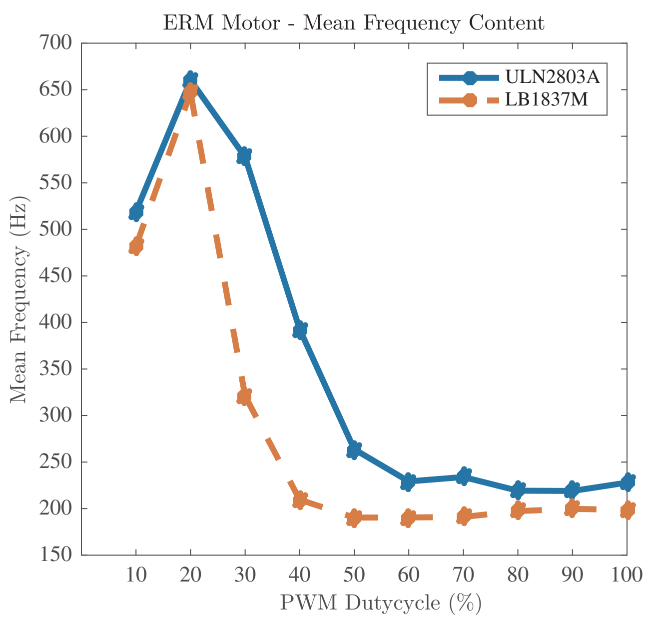


Figure 3.4: The mean frequency content also shows different behaviors between the two ICs: the ULN2803A (blue) shifts the mean frequency value considerably higher for low PWM dutycycles.

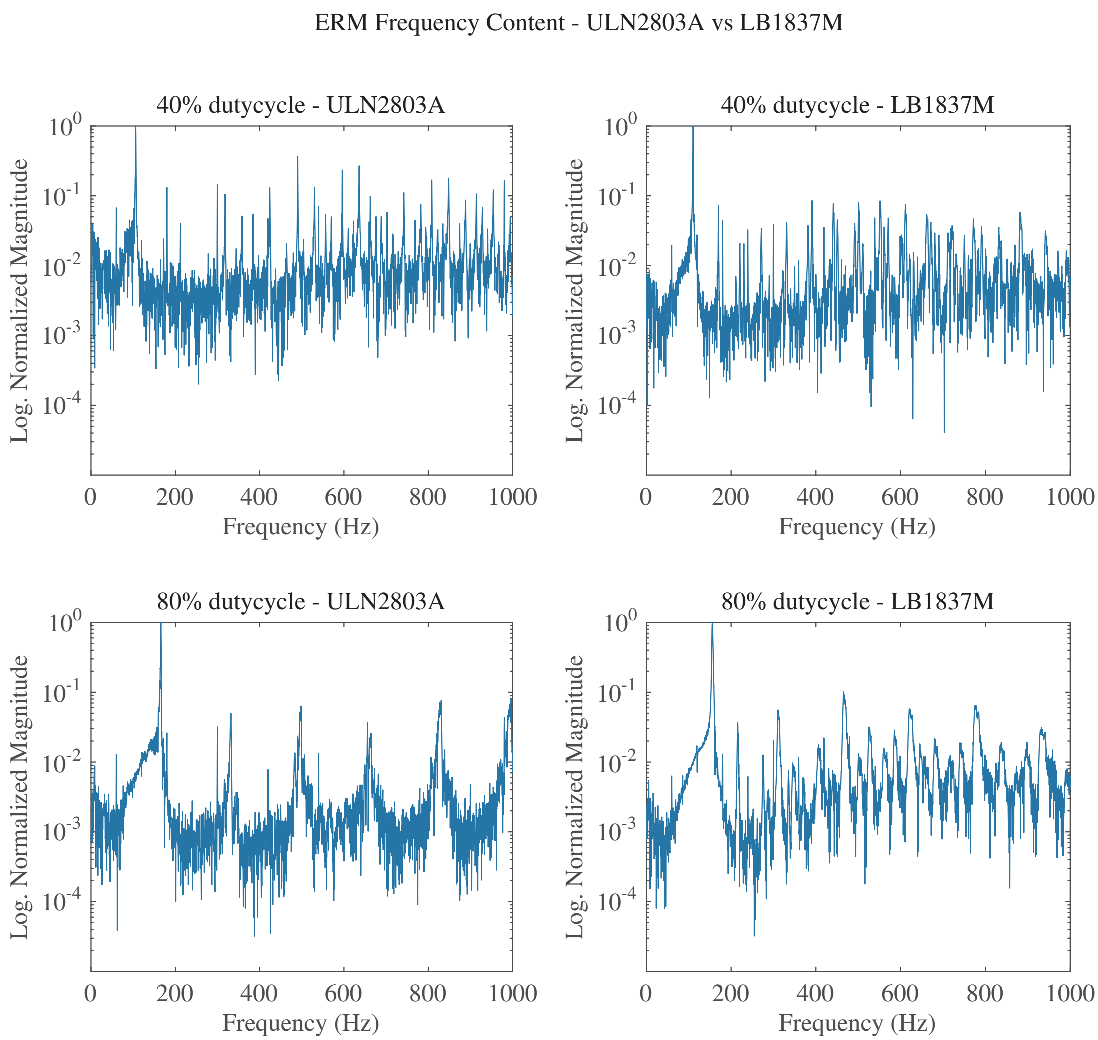


Figure 3.5: The normalized frequency content obtained for two dutycycles (40% and 80%) for the two ICs. We can see that at both dutycycles a more prominent peak is visible around 150 Hz. The ULN2803A driver presents more harmonic distortion, especially at the 80% dutycycle, while the other IC shows a more noisy behavior.

3.3.1.2 Temporal Behavior and Spin-down Time

The driver unit used to control the actuator can have an impact on the overall stability of the vibration and other temporal features, such as spin-down time, i.e. the time required for the motor to reach a full stop after the end of the input signal. This spin-down time is inherent to the mechanics of the motor and can be reduced by using ICs that provide braking functionality, such as the LB1837M. Reducing the spin-down time can help designing sharper tactile effects.

Figure 3.6 shows the raw acceleration data, comparing the vibration decay and spin-down times for the two IC units in the case of a 80% PWM driving signal. It seems evident from the raw data that by using the LB1837M shorter spin-down times can be achieved. With the aim of accurately characterizing the spin-down times for both ICs, we computed an RMS estimation of the signal's energy over time. Using a 1024-sample long sliding window (25% overlap) we could achieve a 6ms temporal resolution. The energy profile for one of the ICs is shown in Fig. 3.7 and it allows an immediate identification of the spin-down region.

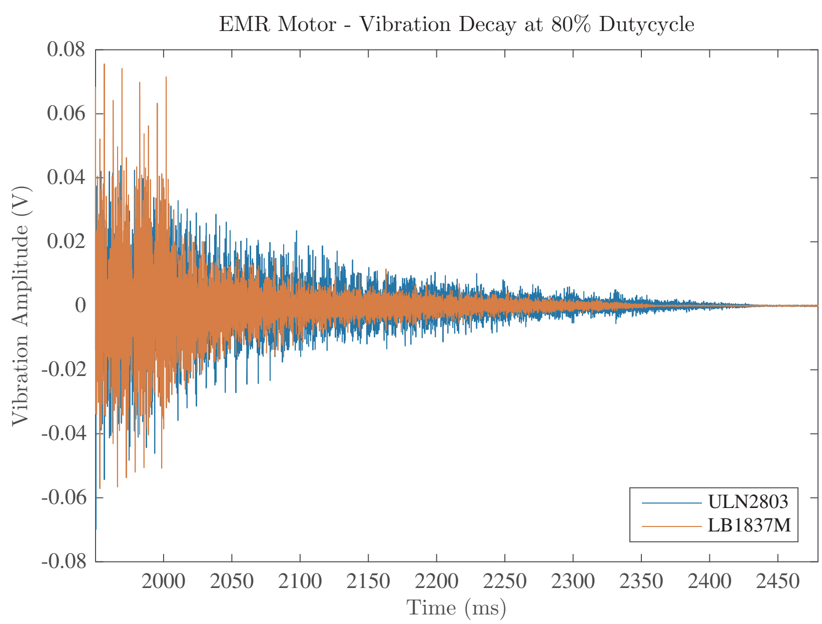


Figure 3.6: Raw acceleration data for an 80% dutycycle vibration. The breaking function of the LB1837M (orange) produces a faster decay compared to the ULN2803A (blue).

The RMS profile was computed for the entire vibration data-set, and the spin-down

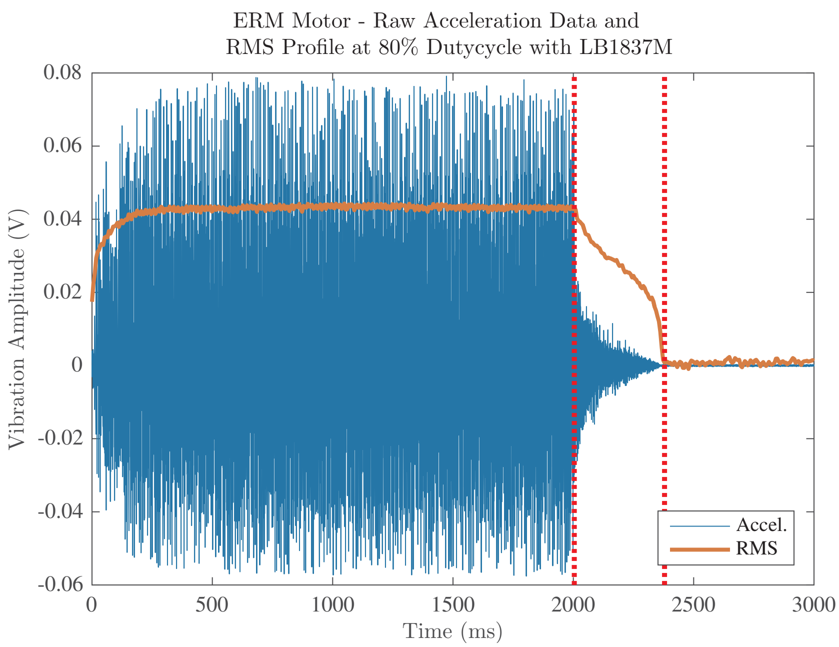


Figure 3.7: The RMS profile (orange) shows the evolution of the energy content of the measured vibration data over time. This provides an efficient way of isolating the spin-down region in which the motor reaches a full stop.

start and end times were extracted from the RMS energy profiles. The final spin-down times can be seen in Fig. 3.8 and in Table 3.1. In nine of the ten considered dutycycles, the LB1837M achieves a faster spin-down, with a relative difference up to 27% lower than for the ULN2803A. For the 20% dutycycle, the ULN2803A is unexpectedly 29 ms faster than the LB1837M. This behavior is quickly reversed and the difference increases for higher dutycycle values.

ERM Motor - Spin-Down Times (ms)										
PWM Dutycycle (%)	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
ULN2803A	18	182	311	369	386	440	445	475	475	498
LB1837M	17	211	275	299	346	351	375	375	381	363
Δ (ms)	1	-29	36	70	40	89	70	100	94	135
Δ (%)	5.6	-15.9	11.6	18.9	10.4	20.2	15.7	21.1	19.8	27.1

Table 3.1: Spin-down times computed for the two motor drivers, with absolute and relative differences, expressed in ms and percentage respectively, in the last two rows. A negative Δ indicates a slower performance for the LB1837M compared to the ULN2803A for the corresponding PWM dutycycle.

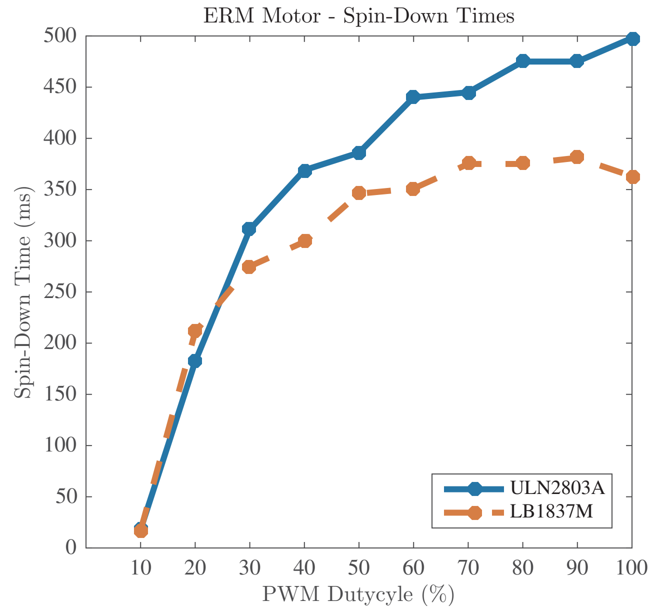


Figure 3.8: Spin-down times for both IC drivers, ULN2803A (blue) and LB1837M (orange).

3.3.2 LRAs

Linear resonant actuators behave, as previously mentioned, as small loudspeaker-like actuators (see Fig. 3.9). A magnetized mass oscillates driven by an AC current flowing inside a cylindrical coil. The mass is compressed against a spring contained in the motor casing, which determines the natural resonant frequency characteristic of the motor.

LRAs have been increasingly used in commercially available tactile-augmented devices. They present several differences compared to ERM motors, which make them more suitable for embedded applications, especially for battery powered devices, while also presenting some drawbacks [Precision Microdrives, n.d.]:

- They provide better energy efficiency when driven at their resonant frequency;
- The driving signal needs to be tuned at the motor's resonant frequency;
- The amplitude output is generally lower than ERMs.

Using a methodology similar to the one used in the previous Section, we measured the physical characteristic of one LRA motor, namely the C01-100 from Precision

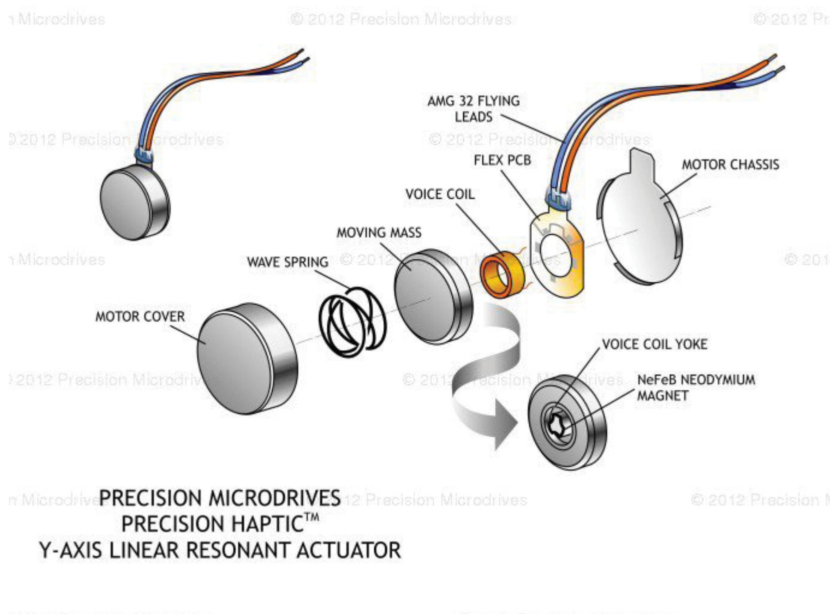


Figure 3.9: The internal schematics of a LRA actuator by Precision Microdrives^{TM} (used with permission).

Microdrives^{TM}[8], using a DRV2605[9] driver circuit from Texas Instruments. This driver provides the user with a pre-programmed library of tactile effects, from which we chose the *"buzz"* effect as testing signal.

This effect comes in 5 distinct intensities, going from 20% to 100% of the intensity range and it was chosen since it provides a constant amplitude throughout the duration of the effect (around 300 ms). We performed amplitude and frequency content measurements as well as spin-down time estimation using the same technique used for the ERM motors.

The Texas Instrument motor driver is capable of driving both LRA and ERM actuators, with signals from the same effects library. The driver automatically translates the input signal to a suitable input signal to be supplied to either an LRA or an ERM, while preserving the properties of the pre-programmed tactile effect. This allowed us to compare the measurements performed on the LRA to the same measurements for the previously characterized ERM motor, driven by the same DRV2605 driver.

[8] `https://catalog.precisionmicrodrives.com/order-parts/datasheet/c10-100-10mm-linear-resonant-actuator-4mm-type`

[9] `http://www.ti.com/lit/ds/symlink/drv2605.pdf`

3.3.2.1 Amplitude Response and Frequency Content

We compared the RMS amplitude of vibration for both actuators at the 5 discrete intensity levels. Results are shown in Fig. 3.10 and demonstrate the higher amplitude vibration provided by an ERM compared to the LRA.

We performed a spectral analysis between 40 Hz and 1000 Hz of the vibration recorded at the 5 intensity levels. The curves showing normalized intensity values for the considered frequency range are shown in Fig. 3.11: the peak at 175 Hz is characteristic of this particular model of LRA and we can see harmonic distortion present in the frequency content, probably due to the mechanical properties of the actuator itself. The magnitude of this harmonic distortion is presented in Table 3.2.

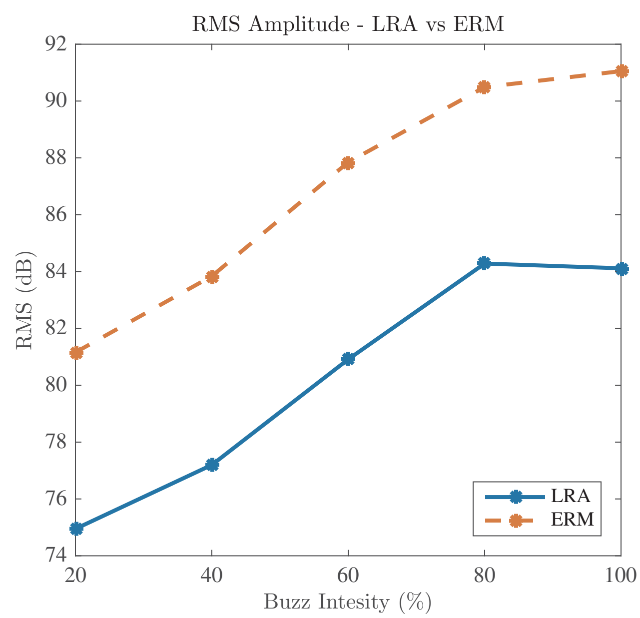


Figure 3.10: RMS amplitude power for both motors at the five discrete frequency steps, LRA (blue) and ERM (orange).

	LRA - Total Harmonic Distortion				
Buzz Intensity (%)	20	40	60	80	100
THD (%)	11.22	4.86	1.08	1.22	1.11

Table 3.2: Total Harmonic Distortion (THD) for the LRA expressed as a percentage. Only the first 4 harmonics have been considered.

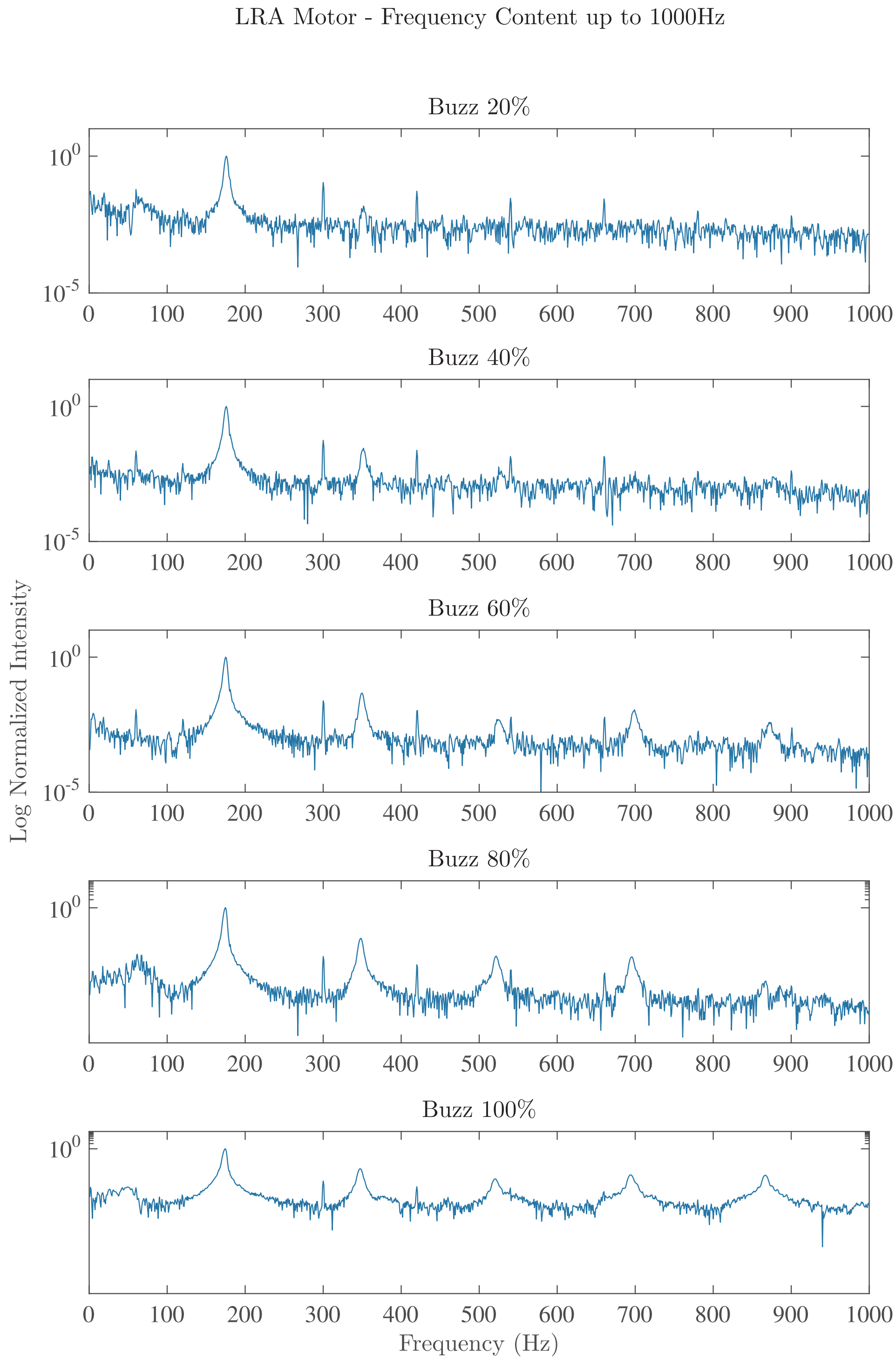


Figure 3.11: Normalized amplitude spectra for the 5 buzz intensities. The resonant frequency for this particular model of LRA is mechanically tuned at 175 Hz. This peak is clearly visible at all intensities and the total harmonic distortion is reported in Table 3.2

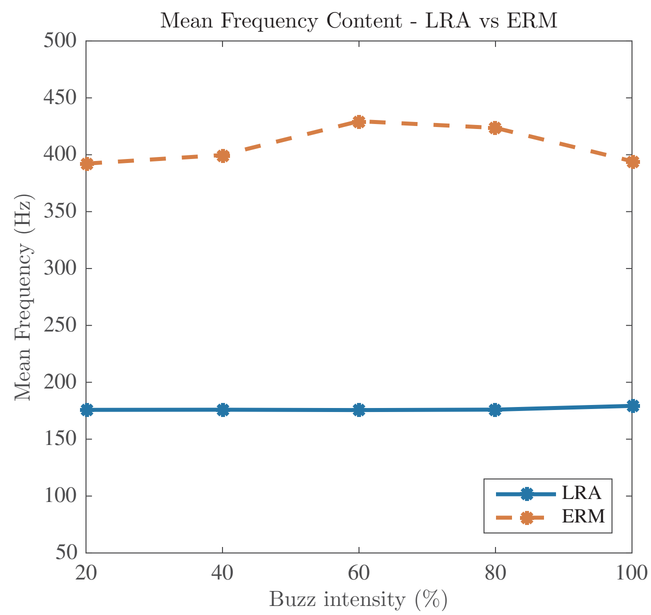


Figure 3.12: Mean frequency content of the LRA (blue) and ERM (orange) actuators at 5 intensity levels of the buzz effect. While the mean value is consistent around 175 Hz for the LRA (value that corresponds to its resonant frequency), the ERM oscillates between 390 Hz and 425 Hz.

The mean frequency content for the LRA is visible in Fig. 3.12, where it is shown together with the same quantity measured for the ERM. Fig. 3.13 shows the frequency content of the ERM for one of the buzz effects. The content presents a noisier behavior when compared to Fig. 3.5, and a similar behavior was measured for all the *buzz* effects for the ERM actuator. This explains why the DRV2605 diver makes the mean frequency output of the ERM oscillate less than the two previously tested driver ICs, as shown in Fig. 3.4.

3.3.2.2 Spin-Down Times

Spin-down times were also computed for the LRA and results are reported in Table 3.3 and plotted in Fig. 3.14. We also computed spin-down times for the ERM motor driven by the DRV2605 IC. The LRA is significantly faster to reach a full stop than the ERM, which is expected since the mechanical design of the LRAs minimizes the effect of inertia. The ERMs' spin-down time for the DRV2605 IC is higher than the one reported for the LB1837M IC, and even higher than the ULN2803A IC, which has no breaking

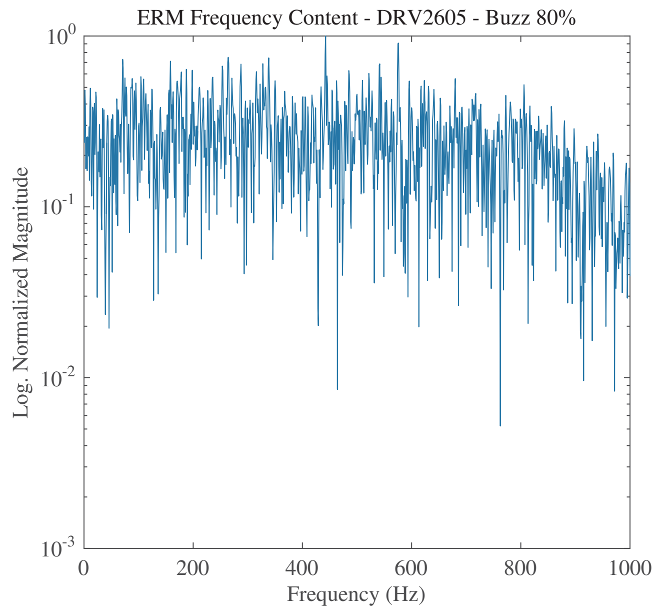


Figure 3.13: Frequency content of the 80% *buzz* effect for the ERM motor. The content is heavily affected by noise, showing a significant difference in behavior compared to the frequency content for the same ERM motor show in Fig. 3.5. A comparable behavior was measured for the other *buzz* effects.

functionality at all. This is due to the design of the buzz effect in the DRV2605 library, which does not implement any braking functionality and presents an ending "tail" before reaching a full stop, for both the ERM (see Fig. 3.15) and LRA input signals.

LRA vs ERM - Spin-Down Times (ms)					
Buzz Intensity (%)	**20**	**40**	**60**	**80**	**100**
LRA	277	282	306	341	341
ERM	417	459	588	676	705
Δ *(ms)*	140	177	282	335	364
Δ *(%)*	50.54	62.77	92.16	92.24	106.74

Table 3.3: Spin-down times for the ERM and LRA motors. The data shows that the LRA is between 50% and 106% faster at reaching a full stop compared to the ERM. Comparison with values in Table 3.1 indicate that the *buzz* effect, as implemented in the DRV2605 IC might have the breaking function switched off for the ERM motors, since the values in this table are considerably higher than those reported for the LB1837M driver. This is confirmed by the analysis of the input signal as shown in Fig. 3.15

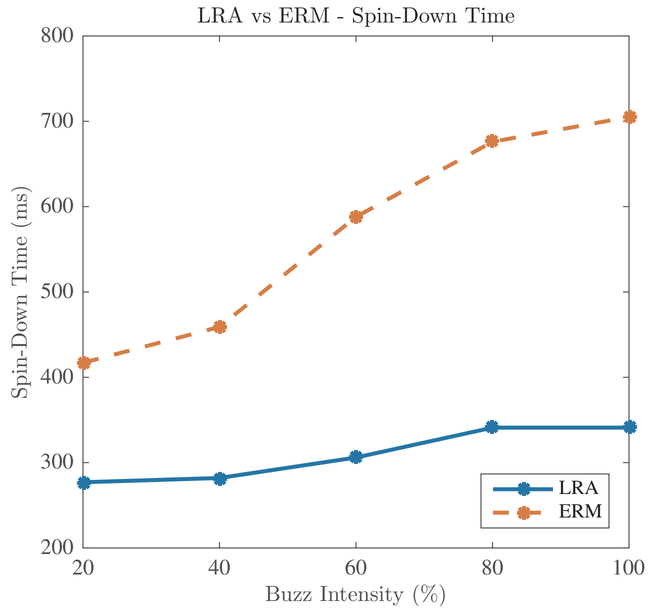


Figure 3.14: Spin-down times for the LRA (blue) and ERM (orange) motors driven using the DRV2605 chip's embedded buzz effect.

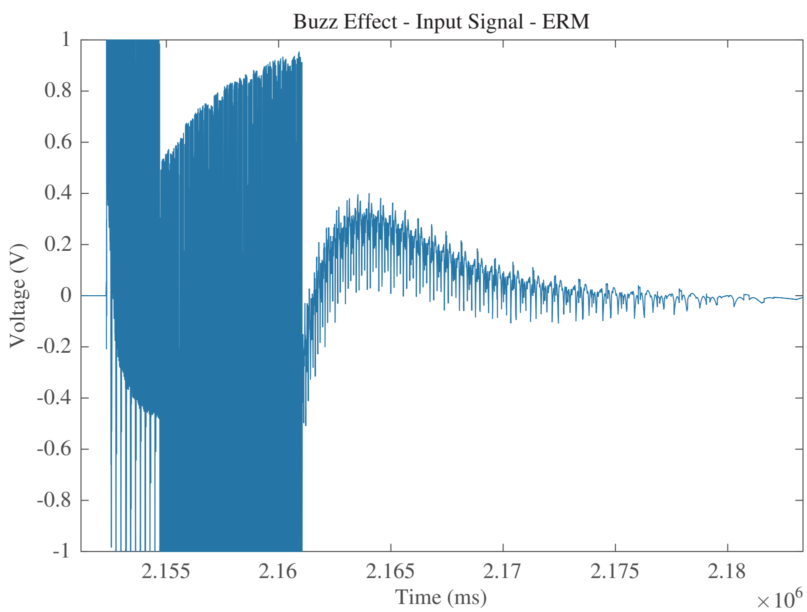


Figure 3.15: ERM input signal for a 100% buzz effect, the longer ending section of the signal translates into a longer spin-down time compared to the two ERM drivers.

3.3.3 Voice-Coils

The voice-coil actuator we predominantly used in the remainder of this thesis is the Haptuator Original[10] by Tactile Labs Inc., which is depicted in Fig. 3.16a. For this characterization, we also considered a custom-built version of the same actuator, following the schematics provided in [Yao, 2004], which can be seen in Fig. 3.16b. The Haptuator is composed of an internal coil of thin, conductive wire, inside which a powerful, cylindrical magnet is free to move in the longitudinal direction. The magnet is held inside the coil by two membranes placed at its two ends. In the commercial version, an external metallic enclosure protects the coil and the membranes, while the custom-built version has the coils and membranes exposed. According to the technical specifications provided by the manufacturer[11], the motor's operational range is between 50 and 500Hz, where the motor is capable of producing up to 3G of acceleration.

The external shell provides an external layer of protection to the thin and delicate wires forming the actuator's coil. The shell, as mentioned, also holds the two elastic membranes on the side, which in turn are attached to core magnet by means of two thin plastic pins (these can be seen in Fig. 3.16a). On rare occasions, these pins can "pop out" of the membrane on one or both sides, causing an unbalanced longitudinal movement of the magnet, and hence possible artifacts in the actuator's vibrational behavior. This side effect of the metal shield is a possible reason for preferring a custom-built version of the Haptuator, especially for applications in which the actuator needs to be permanently embedded into an enclosure. This version features an exposed coil, with no shielding and bigger pins holding the magnet to the external membranes.

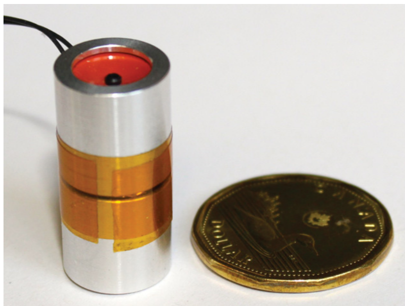
It has to be noted that Tactile Labs Inc. has recently discontinued the Haptuator Original and replaced it with a redesigned version (the Haptuator Redesigned[12]) which address the aforementioned problems by removing the metal shell and more securely fixing the magnet to the external membranes.

We performed frequency domain analyses, focusing on frequency content and frequency response (see Section 3.2.2) of both actuators and of three different power amplifiers: a professional Bryston 2B LP (used as reference), a Sure Electronics PAM8803

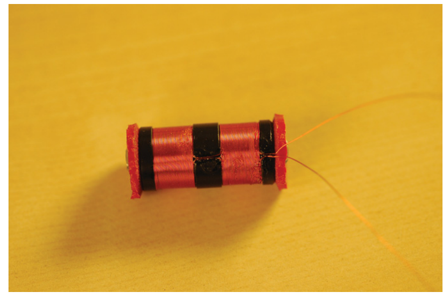
[10]http://tactilelabs.com/products/haptics/haptuator/

[11]http://tactilelabs.com/wp-content/uploads/2012/07/TL002-14-A_v1.2.pdf

[12]http://tactilelabs.com/products/haptics/haptuatorredesign/



(a) The Haptuator Original by Tactile Labs (used with permission).



(b) A custom-built version of the Haptuator (photo courtesy of Joseph Malloch).

Figure 3.16

2 Watt 12 Volt[13], and a custom-build 1 Watt 5 Volt device based on the TDA7052 mono output amplifier IC (design details can be found in [Marshall, n.d.]). The Bryston amplifier is a professional, non-portable solution which guarantees, as we will see, a flat frequency response and was hence used to characterize the behavior of the two Haptuators. The Sure and TDA7052 amplifiers (see Fig. 3.17) are smaller and portable devices that can be easily embedded in augmented interfaces. They are inexpensive solutions (the TDA7052-based amplifier can be built for less than 4$ worth of components, while the Sure model can be purchased for 10$), which guarantee different degrees of fidelity in terms of frequency response.

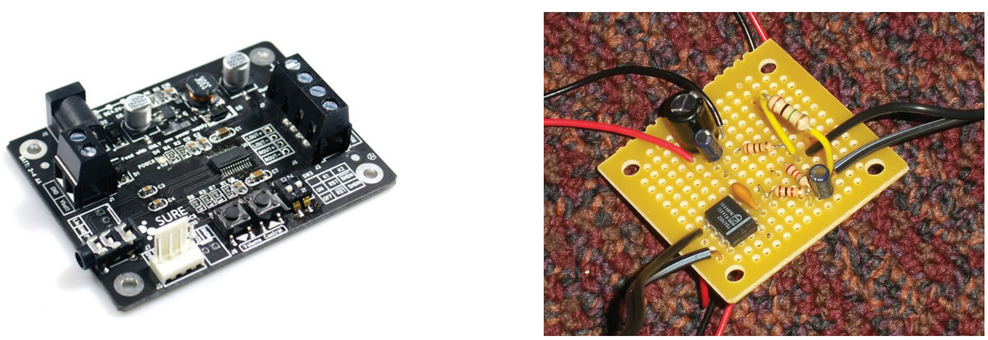


Figure 3.17: The Sure PAM8803 amplifier (left) and a custom-built 5V 1W amplifier based on the TDA7052 chip (right), following the schematics available in [Marshall, n.d.]

[13]http://www.parts-express.com/pedocs/manuals/320-306-sure-electronics-aaab32131-manual-43663.pdf

3.3.3.1 Frequency Content

The three amplifiers were tested using a sinesweep signal, ranging exponentially over time from 20 Hz to 1500 Hz in 1365 ms (see Fig. 3.18) at 0.2V. The input signal was repeated twice, and the output fed into a RME Fireface 400 audio interface, sampling the signal at 48 kHz. The output of each amplifier was also connected to a 6Ω resistance, to simulate the impedance of the Haptuator (according to its technical specifications). The TDA7052 and the Sure amplifier were powered through an external power supply.

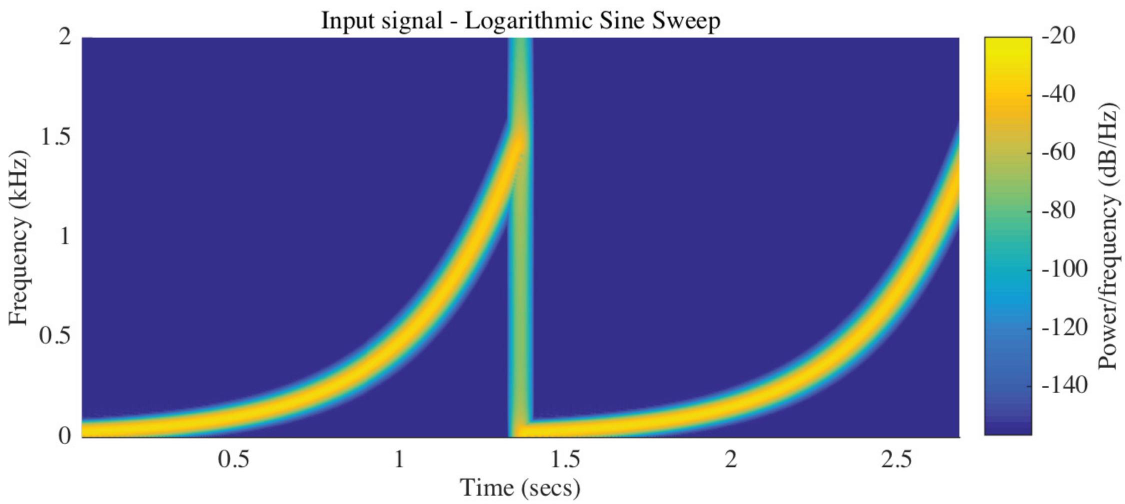


Figure 3.18: Spectrogram showing the frequency content of the input signal used to investigate the frequency response of Bryston and TDA7052 power amplifiers.

The frequency content of the signal recorded straight at the output of the power amplifiers is shown in Fig. 3.19. The Bryston amplifier did not alter the frequency content of the input signal and preserved the frequency amplitude distribution while introducing noise in the order of -120 dB/Hz. The TDA7052 based amplifier, on the other hand, presents a much higher amount of broadband noise and, most importantly, nonlinearities which introduce new frequencies in the output signal. These frequencies are in the order of -50 dB/Hz, and are an indication of the low fidelity of the amplifier itself. The Sure amplifiers also presents distortion in the output signal, but in this case the nonlinearities appear to be less pronounced (in the order of -70 dB/Hz) and the amount of background noise is also less important (-100 dB/Hz).

Subsequently, we connected each actuator to the Bryston amplifier and recorded

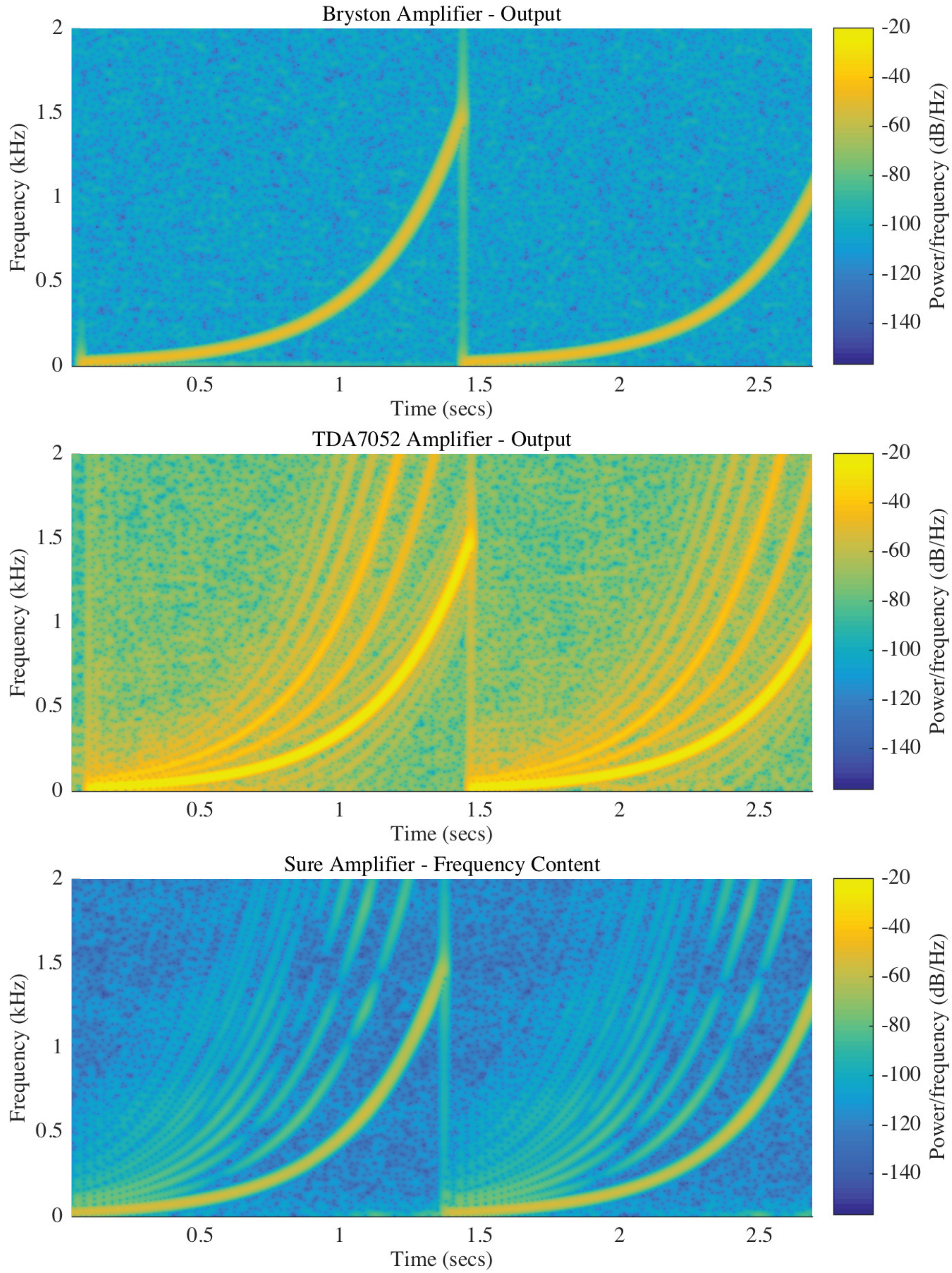


Figure 3.19: Spectrogram showing the frequency content of the signal output from both the Bryston, the TDA7052 and the Sure power amplifiers. The nonlinearities introduced by TDA7052 are clearly visible by the new frequencies introduced in the output spectrum. The Sure presents comparatively less important distortion effects and lower background noise.

their vibration using the same PCB 352C23 1-axis accelerometer used to record the vibration output of the ERM motors (see Fig. 3.20). The input signal fed into the voice-coil actuators was the same 0.2V sinesweep used to characterize the amplifiers.

Figure 3.21 shows the frequency content of the vibration recorded via the accelerometer placed on the body of both the Original and custom-made Haptuators, driven by the Bryston amplifier. The Haptuator Original shows distortion in the order -60 dB/Hz at the output. The custom-made Haptuator on the other hand presents more pronounced distortion, which are clearly visible in the output spectrum and are about -40 dB/Hz.

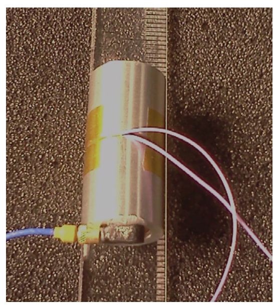


Figure 3.20: The Haptuator Original is fixed to a plastic surface using adhesive petro-wax and the accelerometer is fixed to the metal shell. The accelerometer's sensing axis is aligned to the motor's longitudinal axis.

Discussion When looking at the amplifiers' output, the TDA7052 distorts the output signal in a way that may hinder the design of accurate tactile effects. On the other hand, the main frequency content of the input signal is still predominant in the output spectrum. The same applies for the Sure amplifier, with lower distortion in this case.

If frequency content fidelity is not a requirement, the TDA7052-based amplifier can still be used as a small-scale, low-power solutions. The amplifier's components can be embedded easily into the electronics of the final tactile augmented interface, which is an advantage compared to the Sure amplifier. The latter in fact, while presenting a less distortion, requires a dedicated space to be allocated into an enclosure.

The Bryston amplifier allows, as expected, a high-fidelity representation of the input signal's frequency content. When the interface to be designed does not have portability as a requirement, and the amplifying electronics can reside outside of the interface itself, this type of standalone power amplifiers can be a valuable choice. They are

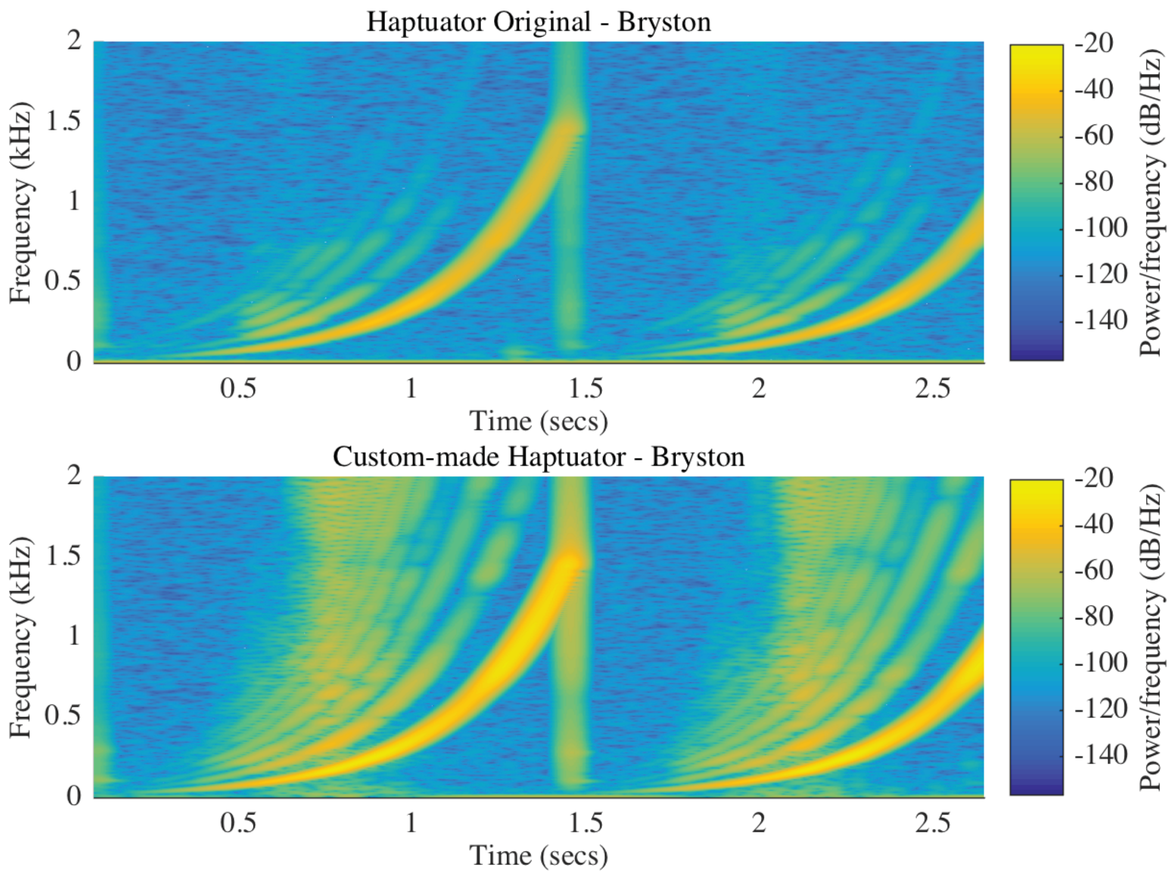


Figure 3.21: Frequency content of the vibration recorded for both motors driven by the Bryston amplifier. Harmonic distortion is visible for both motors, but is more relevant for the custom-made Haptuator.

however much more expensive than the other solutions presented in this Chapter and their choice should be justified by specific needs in terms of frequency content fidelity.

In the context of this dissertation, the Bryston amplifier acts as a reference to properly characterize the behavior of the two Haptuators. Its properties allowed us to use it as the baseline to compare the custom-made Haptuator and the Haptuator Original in terms of their frequency output. Fig. 3.21 shows the frequency content for both actuators up to 2 kHz (i.e. a range that covers the most relevant bandwidth for tactile communication [Verrillo, 1992]).

3.3.3.2 Frequency Response

After inspecting the frequency content of the output signal to detect possible distortion due to nonlinear behaviors, the frequency response can be computed by means of linear transfer functions, provided the system's nonlinearities are weak[14]. We have mainly investigated the magnitude response computed as the ratio of the measured output spectrum over the input signal spectrum for each of the devices.

Firstly we characterized the frequency response of the three amplifiers. The results are depicted in Fig. 3.22, in the 40 Hz to 1000 Hz range. The presence of nonlinearities and background noise present in the TDA7052 amplifier are responsible of the noisiness of the estimated frequency response. The Sure amplifier shows a cleaner response with noise in the higher end of the considered spectrum. These plots, while offering an informative estimation of the behavior of the device, show the need of investigating the output signal as shown in the previous Section. As shown in Fig. 3.19 though, the Sure amplifier introduces nonlinear resonances in the output spectrum, which are not immediately detectable by solely looking at the transfer function approximations.

Secondly, we computed the transfer functions for the two haptuator motors connected to the Bryston amplifier. This allowed us to characterize the behavior of the motor itself, given the neutral response of the amplifier. The responses are depicted in Fig. 3.23

We can see a clearer response for the Haptuator Original, while the response be-

[14] While more complex methods exist to estimate the frequency response of heavily nonlinear systems [Billings, 2013], their use is outside the scope of this thesis. We have limited ourselves to the use of standard, linear techniques to approximate the behavior of weakly nonlinear systems, such as, as we have just seen, the Haptuator motors driven by the Bryston amplifier.

comes noisier for the custom-made version of the motor. As already noted for the amplifiers' responses, this is probably due to the distortion present in the output signal.

Lastly, we connected the Haptuator Original to the TDA7052 amplifier and computed the transfer function in this condition. We subsequently computed an estimation of the same transfer function by multiplying the frequency response of the TDA7052 amplifier alone depicted in Fig. 3.22 with the frequency response of the Haptuator Original as shown at the top of Fig. 3.23. Our estimations treats the combination of the two devices as the linear combination of two filters with known frequency response. The two curves, measured and estimated, are shown in Fig. 3.24. We computed the correlation coefficient for the two curves between 40 Hz and 1000 Hz which returned a value of 0.97, showing that our estimation well approximates the measured response.

This shows that this method can be used to estimate the frequency responses of combined systems, when the response of each one of the parts has already been characterized. This, of course, under the assumption that the combination is linear.

3.4 Conclusions

In this Chapter we presented results aimed at providing guidelines and practical examples for characterizing the properties of several types of vibrating actuators. These actuators can be embedded in pre-existing interfaces to provide vibrotactile feedback and stimulation to users, and the choice of the right actuator technology in the system design is one of the many factors to be considered when designing haptic interactions.

Actuators, and the electronics needed to drive them have the potential to shape the tactile effects they convey in ways that can be unpredictable beforehand. At the same time, the perceptual properties inherent to the sense of touch, which have been described in previous Chapter, represent an additional layer of complexity to add to the task of designing haptic cues. In this context, a complete and thorough characterization of tactile augmented interfaces, both considering physical and perceptual constraints, can be a very demanding task, and is ultimately beyond the scope of our investigation. The results we have shown address, with concrete examples, the impact of several mechanical and electronic properties on the behavior of vibrating actuators, and at

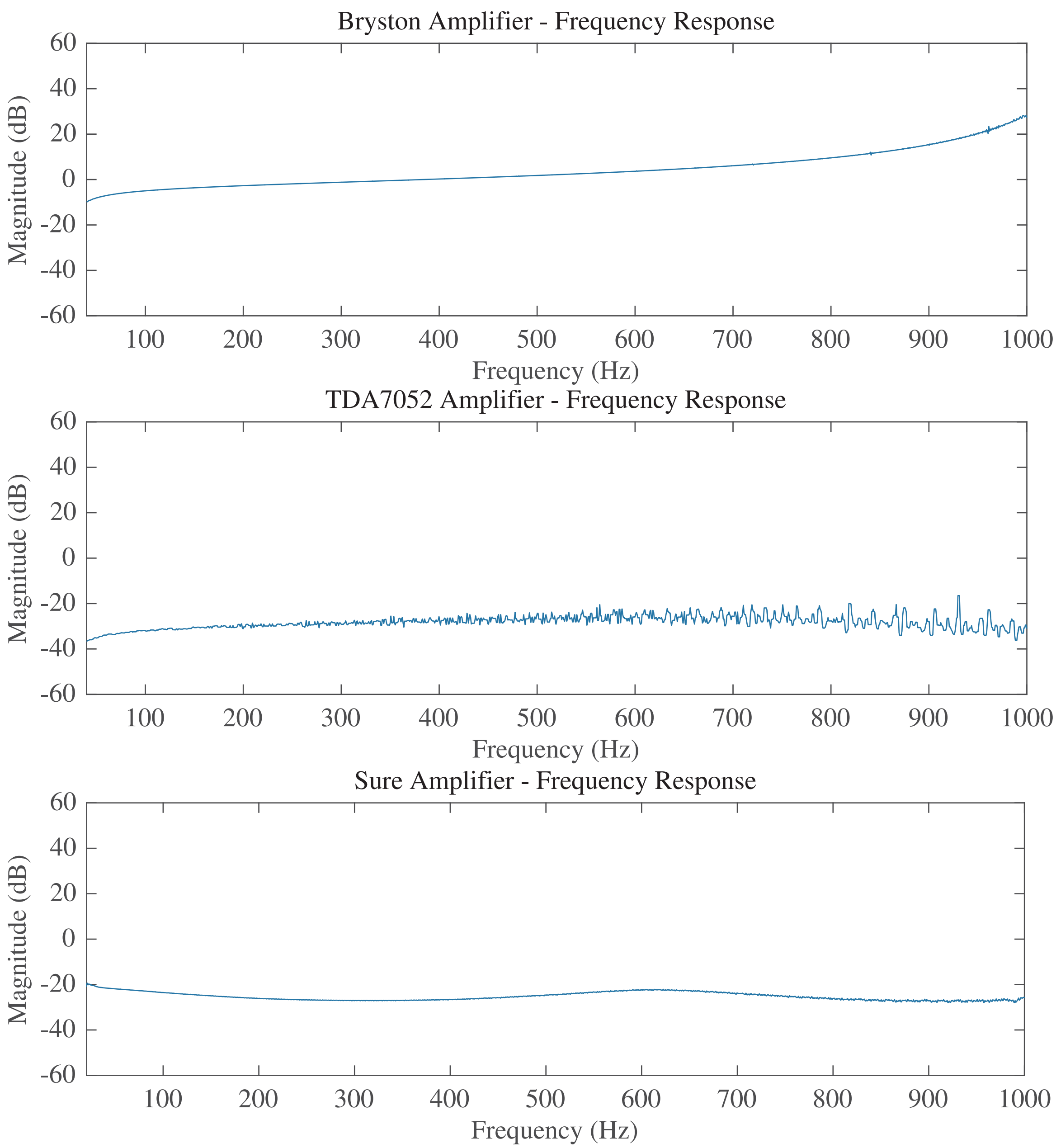


Figure 3.22: Transfer function estimations for the three amplifiers, obtained as the ratio of the amplitude spectrum of the output signal over the spectrum of the input signal. A windowed version of the first half of the input and output signals, respectively shown in Fig. 3.18 and Fig. 3.19, was used. The responses are then smoothed using a 3rd order median filter. The effect of the windowing function is visible at the boundaries, in particular for the Bryston amplifier.

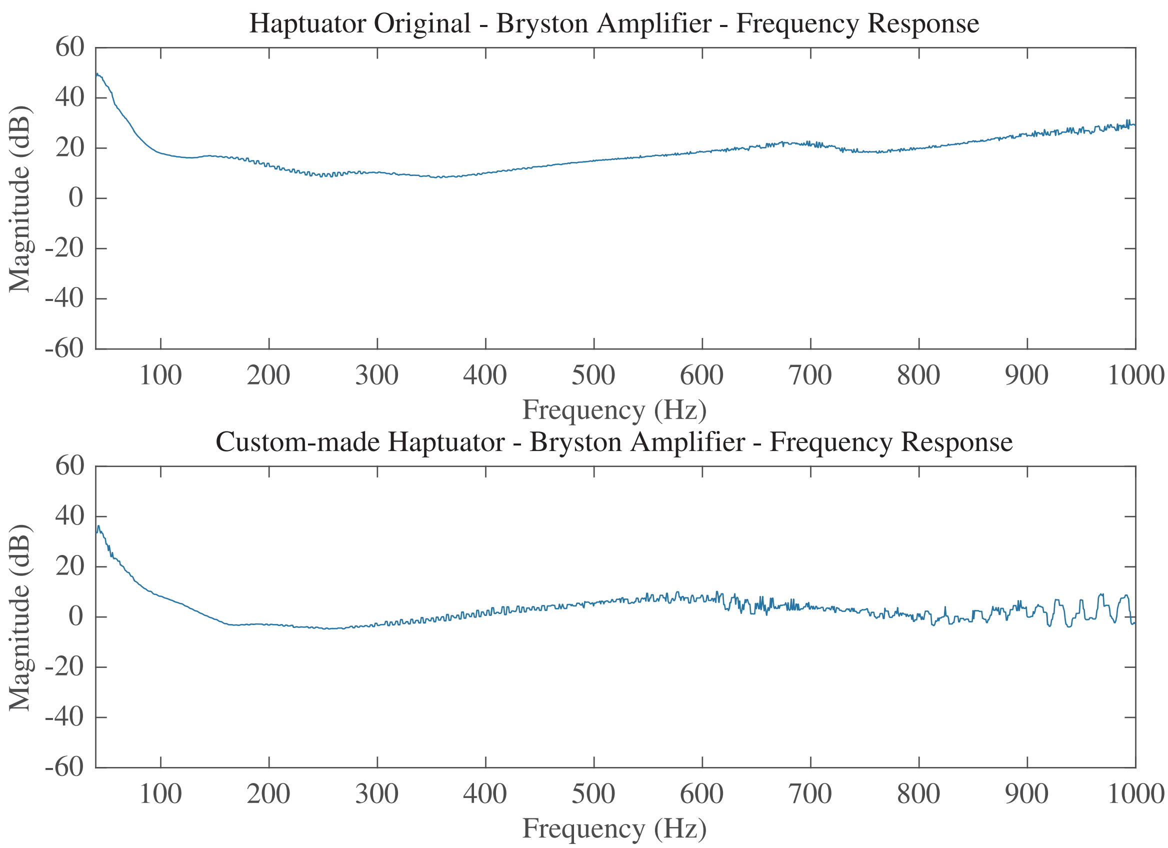


Figure 3.23: Transfer function estimations for two Haptuators connected to the Bryston Amplifier. The responses are smoothed using a 3rd order median filter.

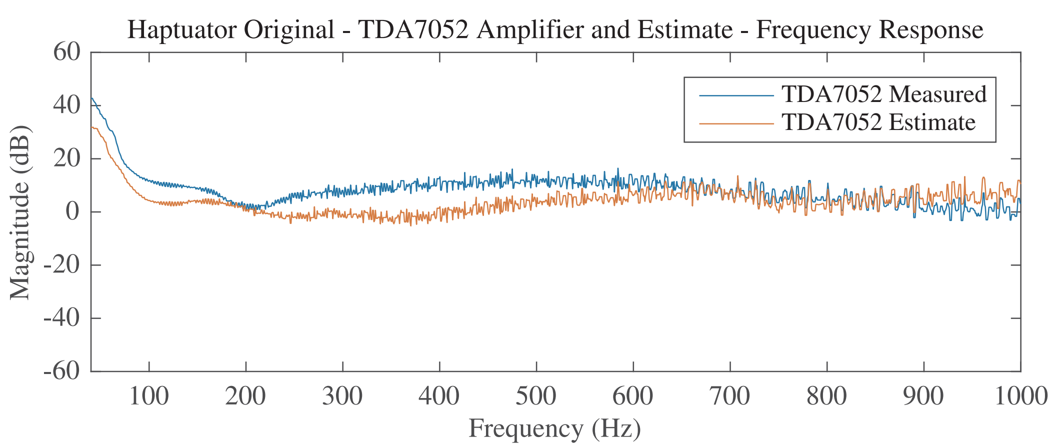


Figure 3.24: The measured and estimated frequency responses of the Haptuator Original connected to the TDA7502 amplifier.

proposing guidelines to characterize these factors.

3.4.1 Guidelines for Actuator Choice

In reference to the taxonomy presented in Section 2.4.4, the results presented in this Chapter allow us to suggest preferred choices for actuator technology to be used in each category:

- Tactile Notification: Given the generally simpler nature of tactile effects in this category, ERMs and LRAs could provide enough flexibility to display meaningful cues. Vibration intensity, or continuous and discrete vibrations could easily be mapped to different notifications (see Chapter 6 for applications in this sense).
  Voice-coil actuators could also be used, especially for notifications using single-site displays. For multiple-site display, power and amplification requirements might make ERMs a more desirable choice.
- Tactile Translation: Voice-coils are the only type of actuator suitable for tactile translation applications, for both sensory substitution and tactile rendering purposes. As we have seen, a frequency response curve needs to be computed to compensate for actuator's and amplifier's properties. Frequency output should also be inspected to determine the amount of distortion introduced in the signal. Several examples in this context are presented in the next Chapter.
- Tactile Synthesis: For tactile synthesis purposes, ERMs, LRAs and voice-coils actuators can all be a suitable choice. ERMs and LRAs can easily be deployed in larger arrays and used to synthesize tactile effects for multiple-site tactile display. Temporal and spatial patterns, as well as intensity and single-actuation temporal envelopes can all be parameters for tactile synthesis (see Chapter 6).
  Voice-coils actuators can also be used for these applications, but the same remarks made for tactile notification apply in this case: these actuators are more suitable for single-site displays, allowing for the synthesis of a variety of tactile effects, but they might not be suitable for a seamless deployment on larger scale.

In the next Chapters we will present several applications of the actuators examined in the previous Sections: the simulation of the haptic behavior of an acoustical musical instrument; frequency compensation techniques; tactile-notification systems to be used in live music performances.

Chapter 4

Haptic Behavior of Vibrating Structures: Characterization and Simulation by means of Voice-Coil Actuators

In this Chapter we present the use of voice-coils as a tool to characterize and simulate the haptic behavior of vibrating structures by analysis and rendering of musically relevant haptic cues, using tactile translation techniques (see Chapter 2). This type of actuators, as shown in the previous Chapter, allow for an independent and accurate control of their frequency output, which makes them ideal for applications such as the ones presented in the following Sections.

In the first Section, we illustrate the results we achieved in enhancing a low-end, force feedback device by embedding a vibrating actuator in its hand effector. This approach can, in a relatively inexpensive way, improve the frequency output of such a device, and hence the amount of haptic cues deliverable to the user. In the given context, the haptic device acts as the physical interface of a DMI, interfacing the user with the haptic model of a bowed string, which produces both the sound and the haptic feedback.

In the second Section, we present the characterization of the vibrations produced on the neck of an acoustic guitar by plucking two of the instrument's six strings. Subsequently, we provide a user-based evaluation of the quality of the rendering of these vibrations by means of a voice-coil actuator. The techniques we describe can have several applications: to evaluate the tactile translation of the vibrations of an acoustic instrument on the body of a DMI [Marshall and Wanderley, 2011]; to provide researchers with tools to investigate the haptic cues provided to musicians by their interaction with a musical instrument [Wollman et al., 2014].

The third Section illustrates the characterization of the vibrational behavior of a wooden floor and its simulation, by means of frequency compensation filtering, onto a portable wooden platform embedded with a shaker actuator. Our approach focuses on an accurate rendering of the low frequencies, to enhance the simulation via the platform of the haptic cues normally delivered by a floor when excited by loud electronic music played in the surrounding environment.

Overall these results illustrate the effectiveness of tactile translation techniques in several applications leveraging the control offered by voice-coil actuators.

4.1 A Vibrotactile Augmented Force-Feedback Device for Bowing Interaction[1]

In Chapter 2, we presented a review of the use of haptic devices in the context of musical interaction and design of DMIs. Several examples included the use of force-feedback devices to simulate the interaction with the model of an acoustic musical instrument.

In this Section we will focus on the application of these devices for the simulation of bowing interaction. We present an enhancement of the SensAble Phantom Omni, a common low-end force feedback device, which features a vibrotactile-augmented handle we built using a Haptuator Original voice-coil actuator. Our intent is to increase the effective bandwidth of tactile information deliverable at the hand of the user, while preserving the capacity for force effects such as friction. We will show that using our vibrotactile augmented set-up, we can overcome the limitations of the Omni, and display frequencies that would be attenuated or completely suppressed by resonance that are inherent to the structure of the device. Ultimately this can provide the player with a better rendering of the behavior of the bowing model.

Since there are many factors to consider in comparing different haptic devices [Hayward and Astley, 1996], we did not attempt to compare the resulting system with exist-

[1]This Section is based on *"Bowing a Vibration-Enhanced Force-Feedback Device"* - M. Giordano, S. Sinclair and M. M. Wanderley - Proceedings of NIME, 2012.

ing high-fidelity devices. Instead, we proceeded by comparing the possibilities of the Omni with and without vibrotactile enhancement during acoustic simulation. We performed frequency content and frequency response measurements of bowing interaction with a one-string model implemented using DISTPLUCK [Sinclair et al., 2011].

4.1.1 Bowed string force interaction

Several works have investigated using a haptic device for bowed string interaction. Florens, [2004] used the Ergon-X system to implement a modal synthesis model based on mass-spring interaction. Berdahl et al., [2009] connected a haptic device with a digital waveguide string model. Serafin et al., [2001] connected the vBow controller [Nichols, 2002] to a physical model of a bowed string. Sinclair et al., [2011] proposed the DISTPLUCK model avoiding some issues with noise in the velocity signal which are found in the aforementioned bowing models. DISTPLUCK was the chosen algorithm we decided to work with since it is robust to sampling issues. For our purpose of synthesizing a bowed string through a vibration motor though, any of these models would have been adequate.

4.1.2 Dual-Channel Haptic Feedback

Our approach to augmenting the frequency content deliverable by the Omni is an example of dual-channel haptic feedback: the Omni motors deliver a portion of the control signal, up to the physical limit determined by the sampling rate of their control signal, while the haptuator is used to deliver the remainder frequencies on a separate channel. A similar approach has been applied to texture interaction, using a voice-coil for vibration actuation [McMahan et al., 2010]. In the context of musical interaction, the only similar musical example we are aware of is the PHASE project [Rodet et al., 2005], in which a force feedback device was augmented using a handle embedded with a voice-coil. The device was used in an art installation aimed at simulating the haptic exploration of the grooves of a virtual vinyl disc.

The architecture of our dual-channel solution is presented in Fig. 4.1, where the two separate control channels are visible at the output of the waveguide bowed string model. The model is calculated at audio rate (48 kHz); the signal is then filtered using a 480 Hz second-order Butterworth filter, before sending it to the Omni motors over its 1 kHz digital control channel. Filtering is necessary to avoid aliasing at the output of the Omni's digital-to-analog converters. Technical details about the modification implemented in the DISTPLUCK model to support this configuration can be found in [Giordano et al., 2012].

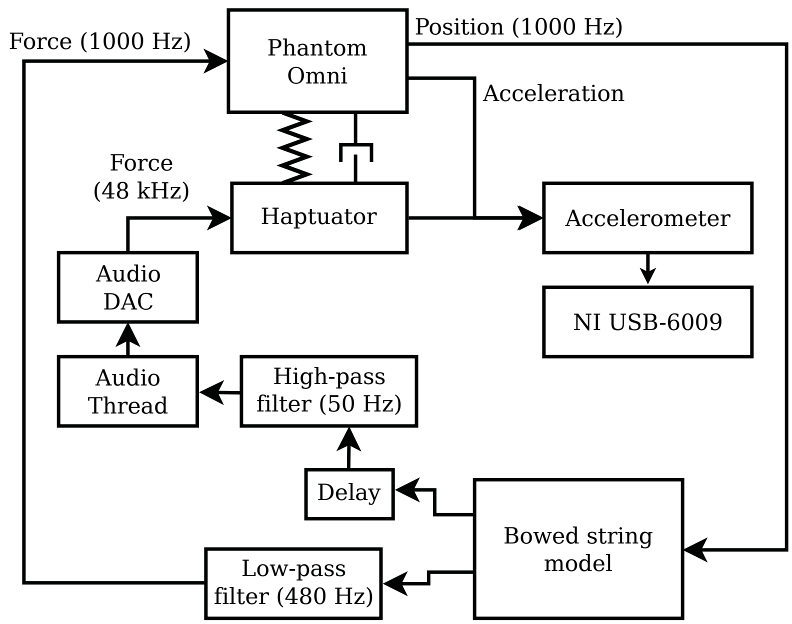


Figure 4.1: System diagram, where position of one horizontal axis implements a velocity driven bowed string model. Vertical axis is not shown, but controls "bow pressure" in the bowed string model (courtesy of Stephen Sinclair).

4.1.3 Experimental Setup

4.1.3.1 Augmented Phantom Omni

The SensAble Phantom Omni haptic device comes, in its factory configuration, with a detachable handle connected to the end effector by means of a one-quarter inch phono connector. This allowed us to replace the existing handle with a custom-built one, embedded with a Haptuator Original (Fig. 4.2).

To build our tactile-augmented handle we installed the actuator inside a plastic pipe of the same diameter as the original handle. A female phono connector, also embedded in the pipe, provided a good connection to the haptic arm.

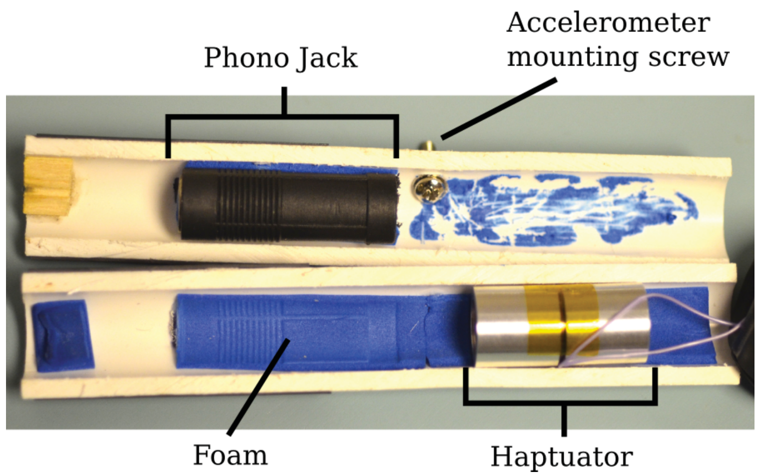


Figure 4.2: Interior of modified handle, showing Haptuator (right) and the phono connector (left).

4.1.3.2 Equipment and Testing Procedure

We used a laptop to control both the haptic device and the actuator, and to record the data. A professional Bryston 2B LP power amplifier was used to drive the actuator. The recordings have been performed using an ADXL202 accelerometer[2], since this model can be tightly secured to the handle with a screw, and connected to a National Instruments USB-6009 acquisition board (see Fig. 4.3). The accelerometer was configured using external capacitors per the datasheet for its maximum bandwidth of 2500 Hz.

Firstly, we characterized the frequency response of the Omni at the handle, with the Haptuator disabled. A two-second long sinesweep at three different intensities was sent to the Omni motors. We recorded the vibration of the device via the accelerometer, orienting it along three different directions (transversal, vertical and longitudinal with respect to the handle).

Secondly, we tested the device in two different conditions:

1. Omni only: As we mentioned, the Omni only accepts a digital control signal sampled at a 1 kHz rate, the frequency content deliverable by the device's motors

[2] `http://www.analog.com/media/en/technical-documentation/obsolete-data-sheets/ADXL202_210.pdf`

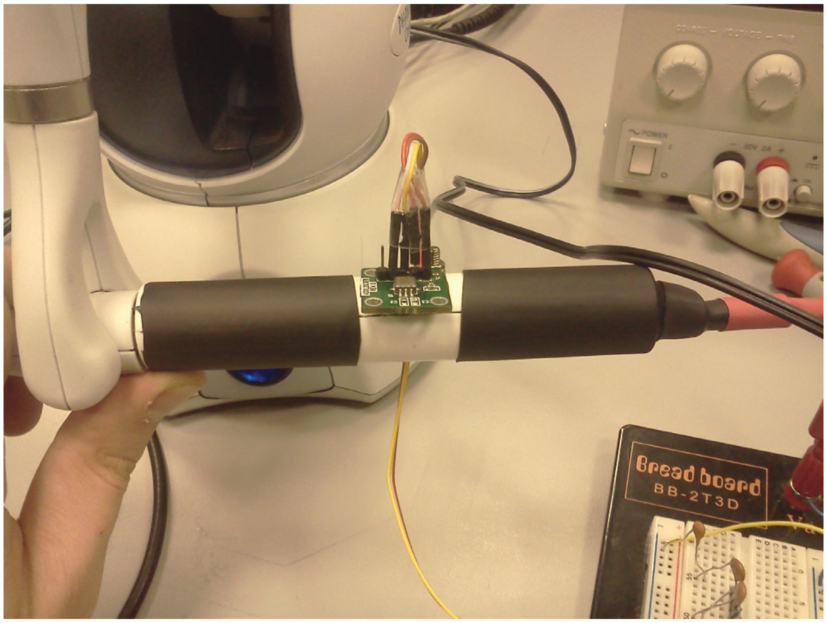


Figure 4.3: The Sensable Phantom Omni with the vibrotactile augmented handle and the accelerometer secured to its mounting screw.

cannot exceed 500 Hz. In this condition, the vibrating handle was turned off and the bowed string algorithm drove the Omni motors with a force signal low-pass filtered at 480 Hz.

2. Omni and Haptuator: The handle actuator was switched on, and the DISTPLUCK algorithm provided a low-frequency control signal to the Omni motors while actuating the handle with the high-frequency portion of the same force signal obtained using a second-order high-pass filter (see sec. 4.1.2).

In this way we hoped to compensate for the resonant characteristics of the device's kinematic chain (see Fig. 4.4), and be able to display more harmonics than with the Omni alone.

4.1.4 Results

The frequency response of the Omni at the handle obtained via sinesweep measurements can be seen in Fig. 4.4. The obtained responses, computed up to 480 Hz, show the effect of the device's mechanical properties on the vibrations perceived at the handle. For instance, an anti-resonance around 100Hz can be seen for the vertical and longitudinal axes of the 0.7V sinesweep.

Subsequently, we analyzed the acceleration recordings in the two conditions: Omni only and Omni and Haptuator. The responses of two similar bowing gestures in each condition were compared for a string tuned to a fundamental frequency of 110 Hz and of 220 Hz.

In Fig. 4.5 we can see frequency domain plots of force and acceleration signals in the two conditions. When the Haptuator was used to deliver high-frequency feedback, the control signal, delivered at 48 kHz, has large peaks for every harmonic of the string. It can be seen that this is well-reproduced in the acceleration.

In comparison, the Omni-only condition required low-pass filtering to be delivered over the 1000 Hz Omni control signal, and this restricted the available harmonics. Moreover, the acceleration does not reproduce all existing frequencies, as it can be seen by the missing peaks at 110 Hz and 330 Hz for the 110 Hz string. There is one distinct peak at 220 Hz, and one at 440 Hz, but the string fundamental is missing, likely due to the anti-resonances we identified in the device's frequency response (Fig. 4.4).

4.1.5 Discussion

In this Section we presented an extension of a commercially available, low-end haptic device, the SensAble Phantom Omni, to replace the device's handle with a tactile-augmented one. The new handle is embedded with a vibrating actuator that can be controlled by an amplified audio signal. We used this augmented device in conjunction with a model for simulating bowed string interaction, so that the added vibration could compensate the device dynamics and control. The device, in its original configuration, operates at a control rate of 1 kHz, requiring the output of the bowed string model to be low-pass filtered. With our enhancement, we allow the higher-frequency portion of the signal generated by the model to be delivered to the actuator, hence compensating for the Omni's inherent limitations.

Using acceleration recordings, we showed that with this approach the range of frequencies displayed is increased, which in turn likely increases the perceived quality of the interaction: violin bow makers state that a bow should be vibrating much [R. T. Schumacher, 1991], but the study of the spectral properties of these vibrations have not

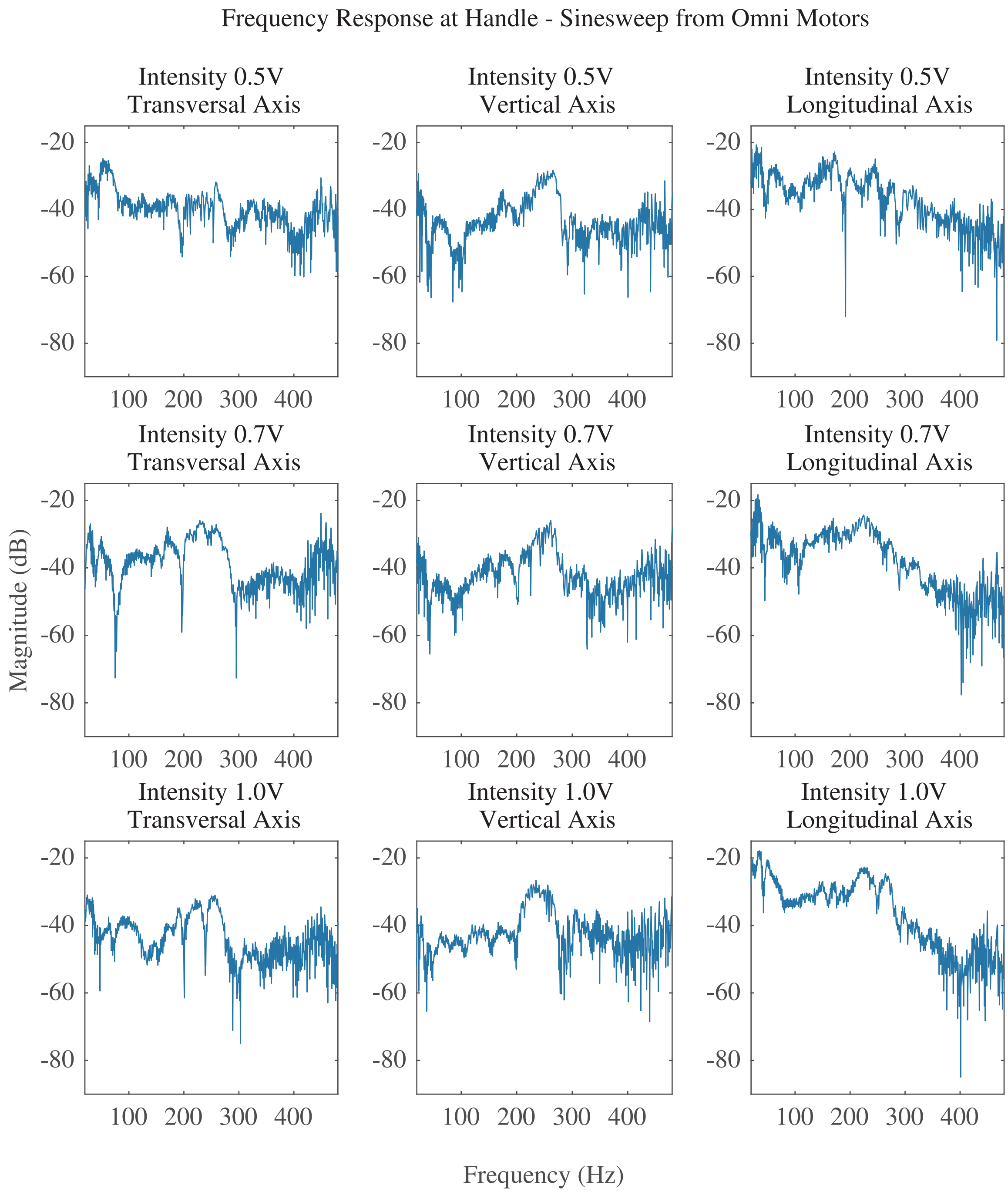


Figure 4.4: Frequency response of the Omni alone at the handle, obtained at three different intensities and along three directions orthogonal to each other.

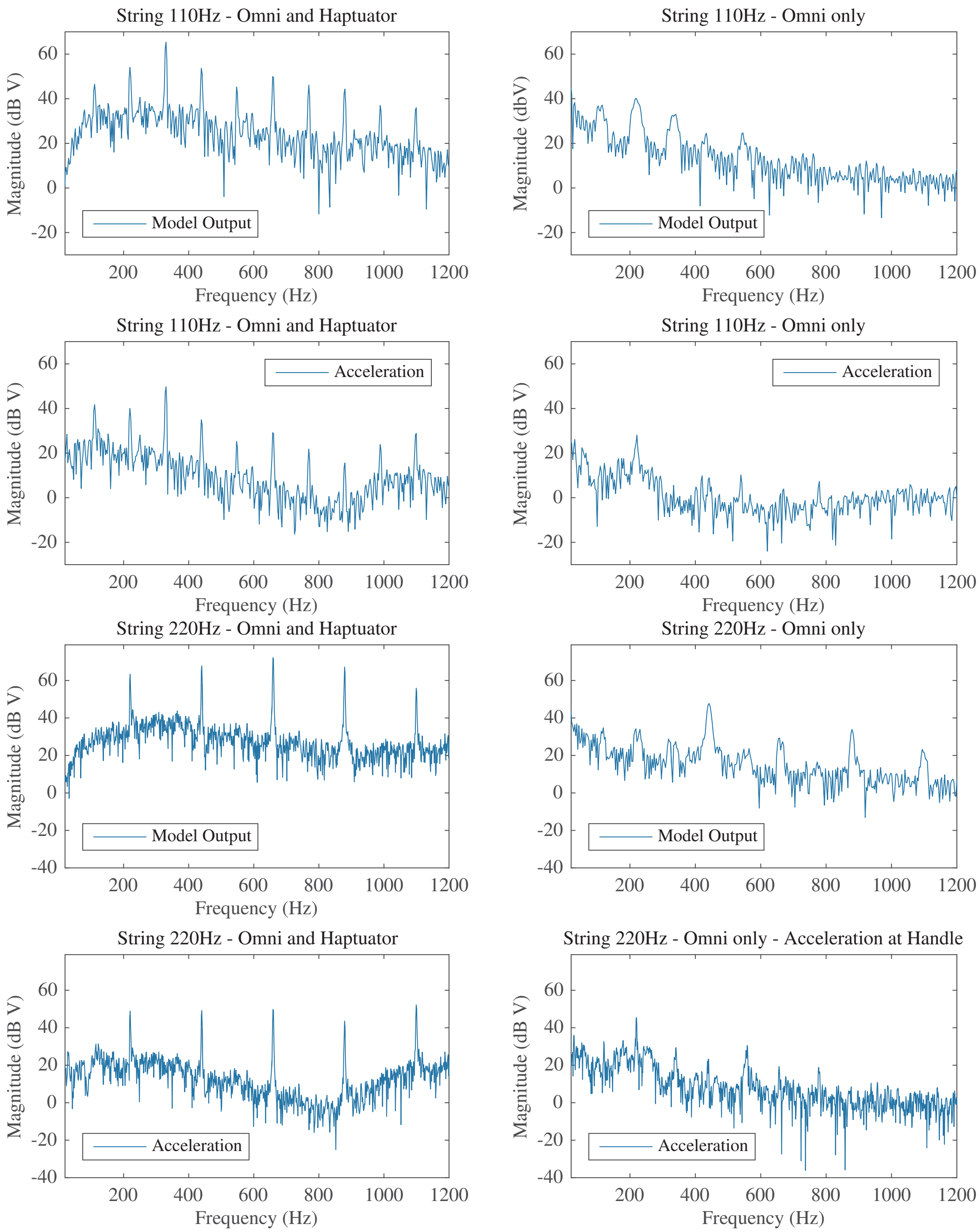


Figure 4.5: Frequency content of force control signal (1st and 3rd row) and measured acceleration (2nd and 4th) for the Haptuator-enhanced Phantom Omni running DISTPLUCK for both a string tuned at 110 Hz (top four plots) and 220 Hz (bottom four plots). Force command voltage for Haptuator (left column, 1st and 3rd plot) is passed through a 100 Hz high-pass filter; force to Omni motors through a 100 Hz low-pass filter. Frequency content of the Phantom Omni without Haptuator enabled (right column, 1st and 3rd plots) is passed through a 480 Hz low-pass filter to match maximum sample rate of digital control.

been conclusive in terms of assessing the perceived quality of a violin bow [Askenfelt, 1995]. In our work, we have not attempted to match the acceleration profile of the device with real-world interaction, as suggested in [McMahan et al., 2010], although this may further improve the realism achievable by these means.

This research question is addressed in the next Section, in which we present acceleration measurements used to model the haptic behavior of an acoustic instrument. A tactile rendering of the recorded vibrations is produced by means of a voice-coil actuator and perceptually evaluated in a user-based test.

4.2 Perceptual Evaluation of the Tactile Rendering of Guitar Neck Vibrations

Haptic cues can have a significant impact on the overall quality of a musical instrument, and can help shape the perceptual properties of the sound produced by the instrument itself [Askenfelt and Jansson, 1992; Keane, 2007]. At the same time, studies have shown that musicians' evaluation of an instrument is often almost exclusively focused on its acoustic properties, while only few qualities can be indirectly associated to the instrument's haptic behavior [Fritz et al., 2010; Saitis et al., 2011; Wollman et al., 2014]. These results suggest that the vibration information, even though available to the player, is integrated with the auditory feedback, making it difficult for the player to give specific judgments about the perceived vibrational properties of the instrument.

As mentioned in Chapter 2, tactile translation techniques can be used to render the vibrational behavior of a musical instrument on the physical interface of a DMI or of an external controller. The aforementioned results suggest that the quality of this rendering could impact the overall judgment of the interaction with the instrument and even shape the perceived sound of the instrument itself. In this Chapter we propose a methodology to characterize and render the vibrations produced by the plucking of two strings onto the neck of an acoustic guitar. We propose a perceptual evaluation of this rendering by means of a vibrating actuator attached to the neck of the instrument. Using this approach, the same actuator could be embedded in the body of a DMI, previously characterized, and allow emulation of guitar vibrations.

Our methodology has two advantages: it provides a simple way to compare real vibrations to actuator-rendered vibration, since they are presented on the neck a real instrument, and it allows participants in our study to hold the instrument naturally, thus producing a more ecologically valid experience.

4.2.1 Experiment

Nine volunteers (two women, nine men) aged from 21 to 55 years old (average 32.8) with various musical backgrounds, were blindfolded and deafened using earplugs and white noise. While holding the neck of the guitar with their left hand (see Fig. 4.9), they were asked to discriminate, only by their sense of touch, between “real” plucks — produced by the experimenter plucking a string with a pick — and synthetic, “fake” plucks — produced by means of the actuator attached to the neck of the guitar.

By comparing the recognition rate of real and fake plucks, we aimed at validating the tactile rendering of string vibrations on the neck of the guitar by means of the Haptuator.

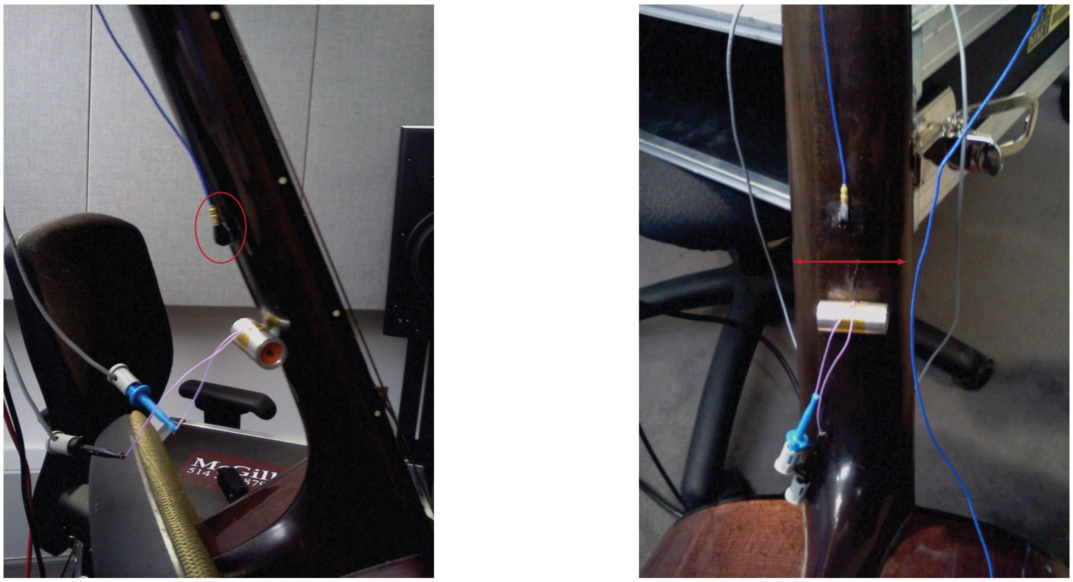
4.2.1.1 Stimuli

We recorded the vibration produced by the plucking of a string using a pick. Two strings were selected, the second (tuned at B_3, $246.94 Hz$) and the fifth (tuned at A_2, $110 Hz$). The plucks were performed using the pick at right angles with respect to the string, whose vibration was hence constrained to the plane parallel to the instrument's body. We recorded the vibration produced by each string for 20 seconds at $24 kHz$ sampling rate, using a National Instruments USB-4431 acquisition card[3] connected to a PCB Piezoelectronics 352C22 accelerometer[4] placed in the upper part of the instrument's neck, approximately 30 cm above the heel. The accelerometer sensing axis was at the same time orthogonal to the strings and parallel to the side of the accelerometer attached to the guitar (red arrow in Fig. 4.6). To introduce variability in the stimuli, we produced four recordings for each string.

A Haptuator Original was attached to the neck of the guitar, 5 cm below the accelerometer, using sticky petro-wax (see Fig. 4.6). The device generated vibrations

[3] http://www.ni.com/pdf/products/us/cat_usb4431.pdf

[4] http://www.pcb.com/contentstore/docs/PCB_Corporate/Vibration/products/specsheets/352C22_G.pdf



(a) Side (b) Front

Figure 4.6: The vibrating actuator and the accelerometers (circled in red) fixed on the guitar. The sensing axis of the accelerometer is aligned with the actuator's longitudinal axis, indicated by the red arrow (front view).

along its longitudinal axis, which was aligned to the sensing axis of the accelerometer, and was used to reproduce the recorded vibrations through the instrument's neck.

The same setup used to record the neck vibrations was used to measure the transfer function between the actuator and the position at which the accelerometer was attached. A linear sinesweep signal, ranging from $30Hz$ to $1500Hz$ in sixty seconds (sampling rate at $24kHz$) was played through the actuator while damping the strings of the guitar. We recorded the acceleration produced by the chirp signal (acquisition rate at $24kHz$). The frequency content of the raw vibration recorded by the accelerometer can be see in Fig. 4.7, plotted between $20H$ and $1200Hz$. As we can see, the recording shows distortion in the lower part of the spectrum (around $200Hz$), but the extent of the nonlinear behavior is limited. We hence computed a transfer function, as shown in Fig. 4.8, again between $20Hz$ up to $1200Hz$, a range that covers the frequency sensitivity for the skin on the hand [Verrillo, 1992; Oey and Mellert, 2004].

The previously computed transfer function (Fig. 4.8) was inverted and used as a compensation filter to re-equalize the recordings of the plucks, exported as wave files. This step was necessary to ensure that, once played through the actuator, the

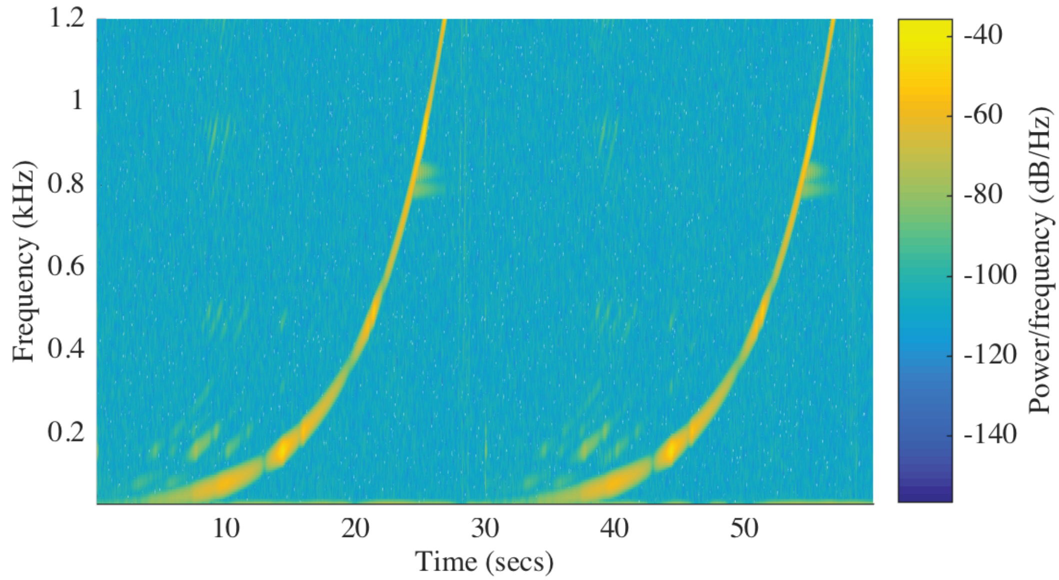


Figure 4.7: Frequency content of the vibration recorded by the accelerometer while the neck is excited using a linear sinesweep.

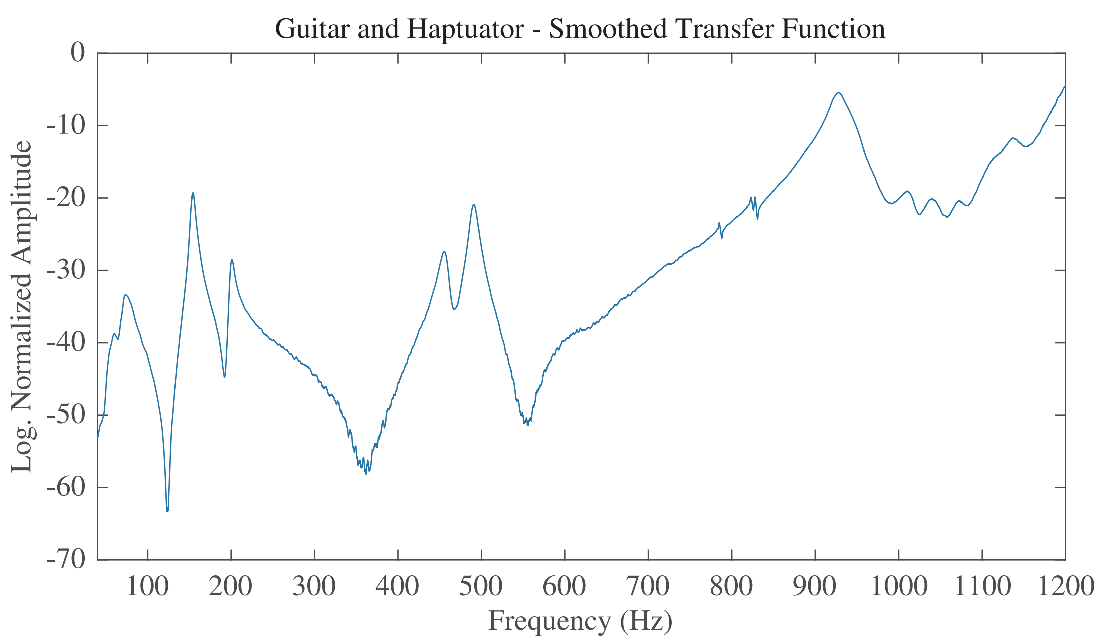


Figure 4.8: Transfer function between the actuator and the accelerometer, measured while damping the strings, smoothed with a 3rd order Savitzky-Golay filter.

recorded vibration would be perceived with the same frequency characteristics as those produced by a real pluck, at least at the point where the accelerometer was located.

4.2.1.2 Procedure

The experiment was divided into two separate phases, each associated with a specific task. In each phase, participants (wearing blindfolds and headphones playing white noise) were holding the guitar with their left hand, without touching the strings, at the point were the accelerometer was placed in the stimuli recording session (Fig. 4.9).

(a) One of the participants during the experiment.

(b) Hand detail.

Figure 4.9: Experimental setup

In Phase 1, after familiarizing themselves with the vibrations produced by the plucking of the second and the fifth string, participants were asked to discriminate, only via the sense of touch, which string had been plucked by the experimenter using a pick. A series of twenty randomly ordered plucks were proposed and participants verbally reported which string they thought had been plucked at each trial. This task served to assess if participants could discriminate between the two strings solely by the sense of touch. A threshold of 80% recognition rate was set as minimum requirement for a participant's data to be further analyzed.

In Phase 2, participants were asked to discriminate between a "real" pluck performed by the experimenter, and a "fake" pluck, consisting of the reproduction via the actuator of one of the recordings. They were not asked to identify to which string the vibration corresponded to, and they were not exposed to any trial vibration coming from the actuator. A series of forty, randomly ordered stimuli (twenty real and twenty fake plucks) was proposed and participants verbally reported if they thought they had just perceived a real or fake pluck.

4.2.2 Results

We conducted a descriptive statistical analysis of the collected data to verify the rendering of the string vibration.

Firstly, we looked at participants' performance in phase 1 to determine if the minimum threshold of 80% recognition rate had been reached. As shown in Fig. 4.10, participants met the 80% threshold, with an average recognition rate of 96.7%.

Secondly, we looked at the data for phase 2, and firstly examined the percentage of real plucks correctly identified as such, and found a rate of correct answers across participants of 74.14% (standard deviation: 11.36). This shows that participants' ability to determine a real pluck is above chance.

We then looked at the recognition rate of fake plucks, i.e. those produced by the actuator for each of the two considered strings.

We removed outliers in the data and performed a Shapiro-Wilk test which failed to reject with a 5% significance level that the data does not belong to a normal distribution. We then applied a one-way analysis of variance to investigate the effect of the string on participants' recognition rate. Results showed the effects of the string ($F = 4.98; p < 0.05$) was significant, as suggested by the data depicted in Fig. 4.11 and in Table 4.1.

	Rec. Rate - Actuator Only	
	String 2	**String 5**
Median (%)	81.82	50
Mean (%)	74.58	51.55
S.D.	23.53	20.11

Table 4.1: Per-string recognition rate for actuator plucks correctly recognized as fake in both phase 2 and phase 3.

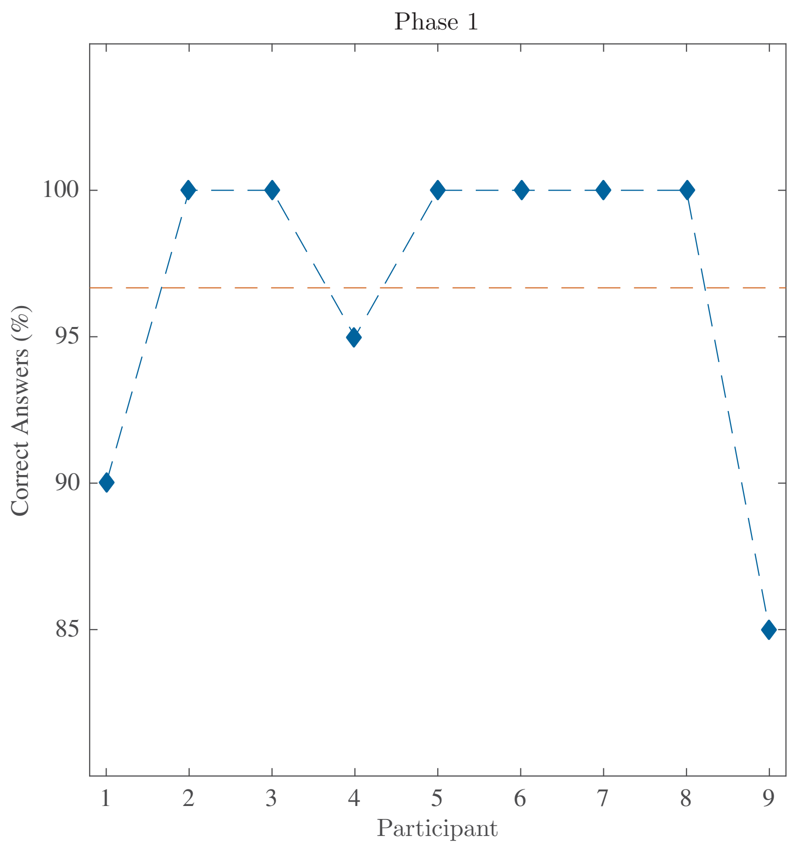


Figure 4.10: Results of experiment phase 1, with mean value plotted horizontally. All participants met the 80% threshold.

These results show that the actuator's simulation of the string 2 was not good enough, since we have an average identifications of fake pluck of 74.58%. On the other hand, the simulation of string 5 seems to be substantially better, with an average just above chance (51.55%). We notice a fairly high variability of the data, as indicated by the standard deviation (S.D.) values.

4.2.3 Discussion

We have shown that our tactile rendering technique produced better results for the low-pitched string than for the high-pitched one. This could be due to mechanical limitations of the actuators in displaying higher frequencies or to the fact that we recorded the vibrations only along one axis of the neck.

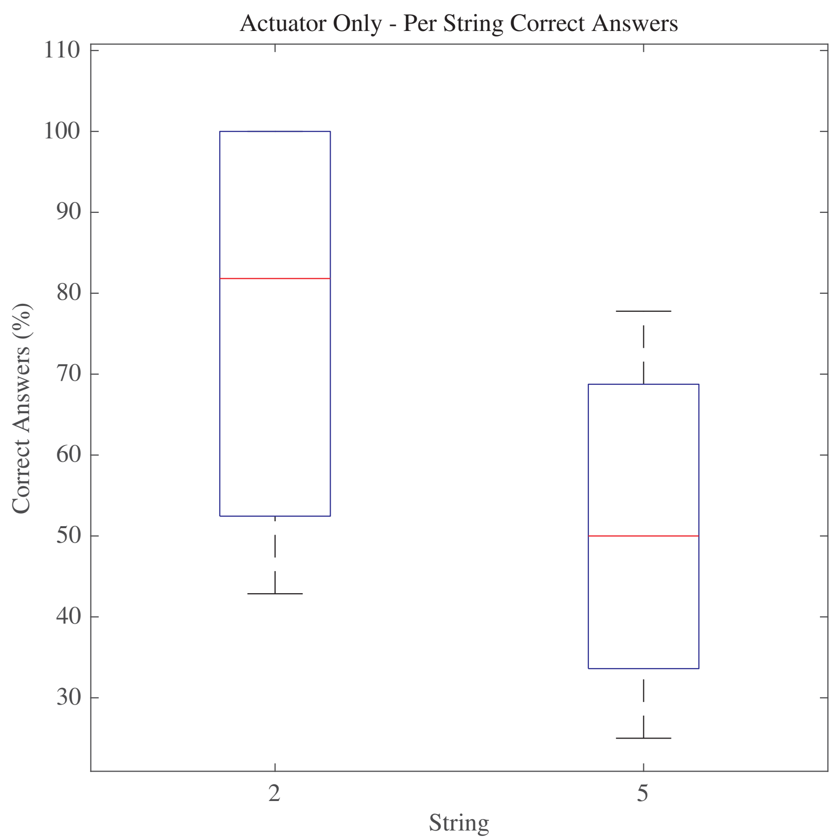


Figure 4.11: Percentage of "fake" plucks correctly identified as such for both string 2 and string 5.

Of particular interest for future improvements in our design were the comments participants gave in an informal interview that followed the test:

- At the question *"how well do you think you performed?"*, participants unanimously agreed that the test was very difficult and they thought to have performed at chance level.
- When asked about the criteria they used for taking their decision, resonance time and the attack emerged as being the most important cues: longer resonance times and weaker, less pronounced attacks would feel unnatural. Interestingly 2 participants identified the same criteria as being the most important ones, but in the beginning longer resonances and weaker attacks would be associated for them to real plucks; further on in the experiment they eventually switched their judgment.
- Overall, they stated that they could not find very strong cues for determining if a pluck was real or not.

Our findings show nonetheless that the approach we proposed can lead to an acceptable rendering of the haptic behavior of the instrument, at lest for the tested low-pitched A string.

4.3 Frequency Compensation Techniques for the Simulation of the Vibrational Behavior of a Wooden Floor

In this Section we describe the design and construction of a wooden platform embedded with a voice-coil actuator, specifically tuned to deliver low-frequency vibrations. Such a device is often referred to as a "shaker" and is used in media applications to augment, for instance, cinema chairs to deliver vibrations to the audience.

The platform (see Fig. 4.15) was built in the context of a multidisciplinary research project[5], conducted in collaboration with the Montreal Neurological Institute (MNI) and the International Laboratory in Brain, Music and Sound Research (BRAMS). Researchers at the partner institution — Martha Shiell from the MNI and Pauline Tranchant from BRAMS — aimed at investigating the role of vibrotactile cues in the per-

[5] http://www.cirmmt.org/activities/newsletter/november13

ception of a musical beat. The experiment was conducted on a profoundly deaf population as well as control normal-hearing people. Participants were asked to stand on the platform and bounce synchronously with a musical beat delivered to their feet by the shaker. Their movement was recorded by 12 infrared motion capture cameras to be subsequently analyzed.

To conduct the experiment, the partner researchers required a device capable of: producing a vibrotactile stimulus simulating the experience delivered by a real wooden floor when loud music is playing from nearby speakers and subwoofers; producing minimal levels of auditory feedback.

In order to build such a device, we performed measurements on a real wooden floor, excited by a subwoofer, to characterize its frequency response. We then designed and assembled a wooden platform, augmented via a shaker actuator and designed an offline compensation filter to reproduce the vibrational behavior of the real floor onto the platform.

4.3.1 Floor Characterization

We performed our measurements on a wooden floor in one of the research labs at the Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT). A one-dimensional PCB Piezoelectronics 352C22 accelerometer and a Genelec 7070A active subwoofer[6] were used to perform the measurements. The accelerometer was placed on the floor with its sensing axis orthogonal to the floor itself and at 1.5 m distance from the subwoofer (see Fig. 4.12). The excitation signal used was a four-second long, double sinesweep signal, whose frequency increased exponentially from 20 Hz to 300 Hz. The amplitude of the sweep was set at 0.25 V, corresponding to the median amplitude of the stimulus used for the final experiment.

The output voltage produced via the accelerometer was acquired via a National Instruments USB-4031 card. To take into account the floor deformation due to the weight of a participant, the recording session was performed with the experimenter standing on the floor, with the accelerometer between his feet.

After inspecting the output signal for the presence of non-linear resonances, a standard frequency response was computed for the floor response as depicted in Fig. 4.13.

[6] https://booking.cirmmt.org/media/model/308/7070a.pdf

The frequency range we analyzed goes from 30 Hz to 170 Hz. This is due to the fact that most of the energy of the stimuli to be used in the final experiment (a techno-sounding musical excerpt, with a well defined, low-frequency beat) is included in this range (see Fig. 4.14).

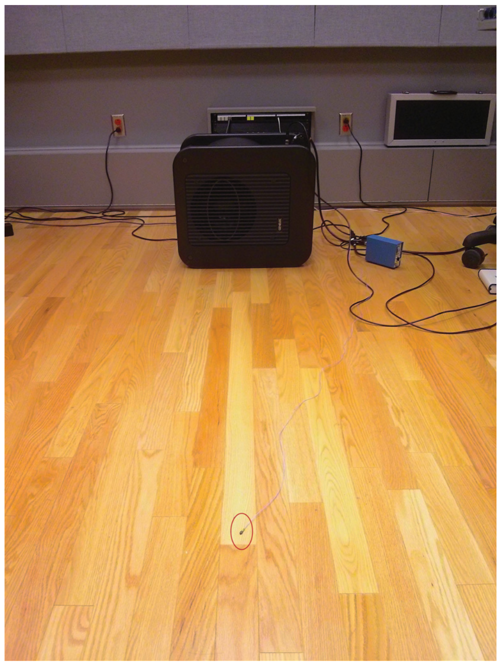


Figure 4.12: Floor characterization setup with the accelerometer (circled in red) placed at 1.5 m from the subwoofer.

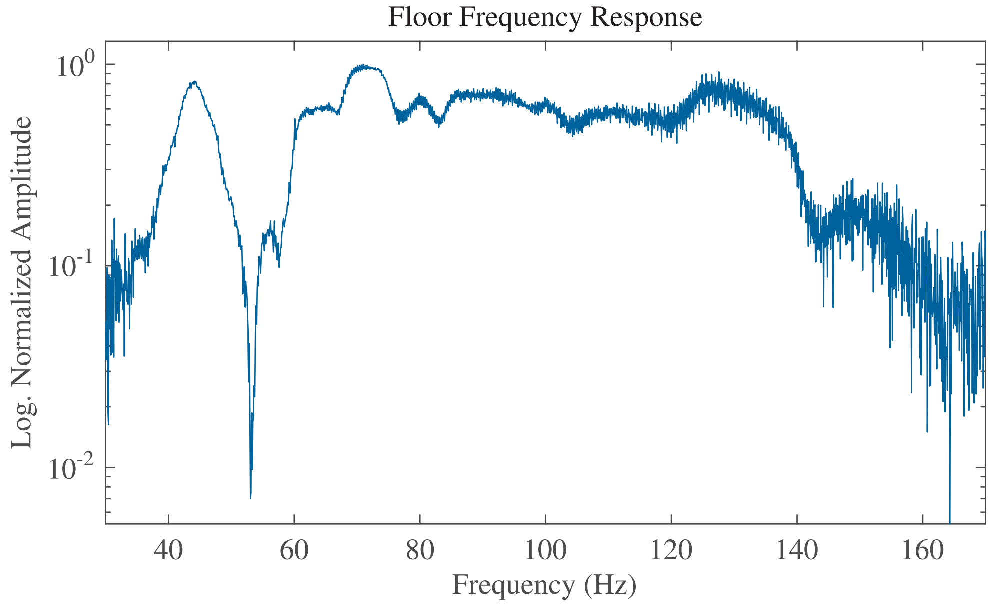


Figure 4.13: Frequency response of one of the CIRMMT laboratories wooden floor from 30 Hz to 170 Hz.

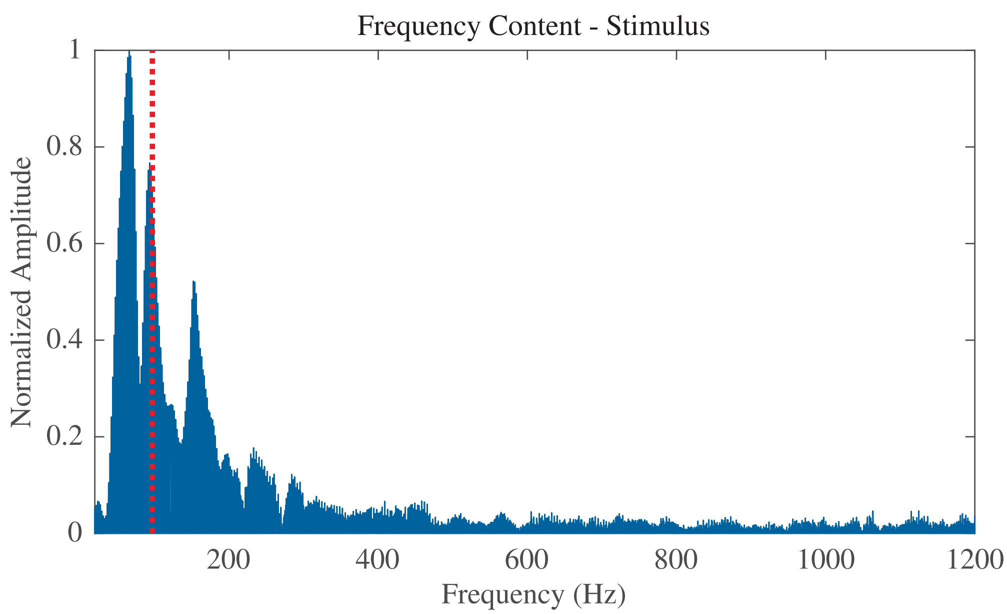
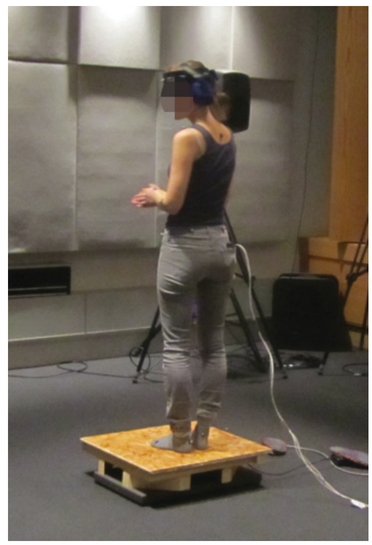


Figure 4.14: Frequency content of the stimulus used to test the deaf and normal-hearing population in the final phase of the experiment. The median frequency content of the signal is 97.16 Hz (red dashed line).

4.3.2 Platform Design and Characterization

The platform was designed to be robust and easily portable, while featuring off-the-shelf and inexpensive materials. A 60 cm by 60 cm plank made of composite wood was raised using eight 5 cm thick wooden bars, glued and then tightly screwed to the plank. A Clark Synthesis TS209 Tactile Transducer[7], was also tightly attached at the center of the plank, and connected to a Sure PAM8803 amplifier[8], characterized in Chapter 3.

(a) Bottom of the platform with the TS209 securely attached by four screws.



(b) One participant testing the platform.

Figure 4.15

The same methodology described in the previous Section was applied to characterize the vibrating behavior of the platform. The accelerometer was fixed on the center of the platform and the previously described sinesweep was fed into the TS209. The experimenter stood on the platform, whit the accelerometer lying in the middle of his feet, while recording the plank's vibrations [9].

[7]http://www.parts-express.com/pedocs/specs/300-861-tactile-sound-tst209-specifications-46286.pdf

[8]http://www.parts-express.com/pedocs/manuals/320-306-sure-electronics-aaab32131-manual-43663.pdf

[9]This was done to take into account the deformation applied to the plank by the weight of a person standing on it. During the actual experiment, participants would perform a "bouncing" movement, hence dynamically deforming the plank. We estimated that the stiffness of the wooden plank would guarantee a sufficient rigidity of the system, and we only characterized the platform in a static weight condition.

The frequency response of the device is plotted in Fig. 4.16. The response presents less noise compared to the response computed for the floor. This can be explained by the fact that the accelerometer was closer to the source of the excitation signal in the case of the platform.

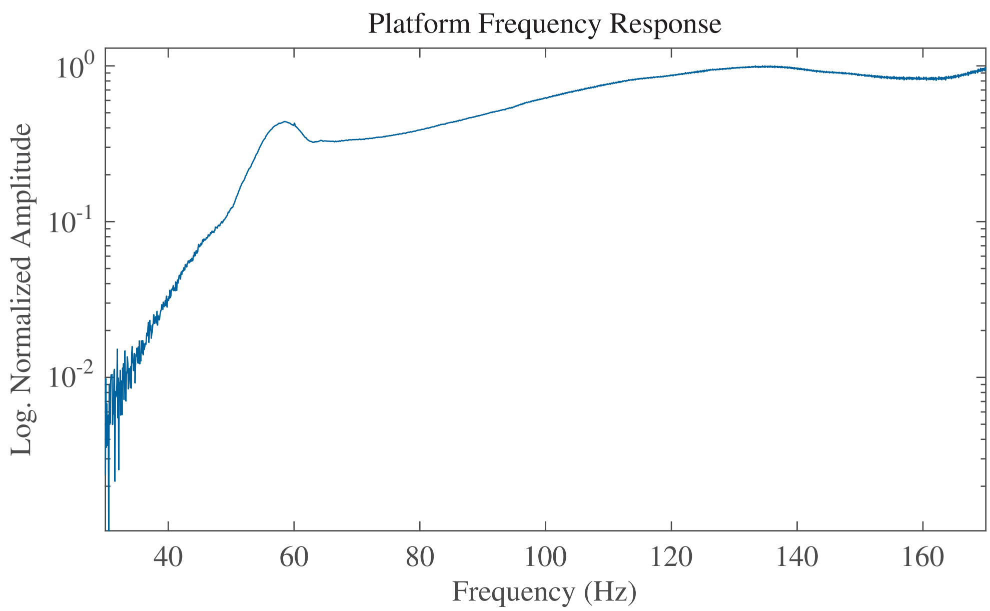


Figure 4.16: Frequency response of the wooden platform augmented with the TS209 actuator, computed between 30 Hz and 170 Hz.

To derive the amplitude response of compensation filter needed to make the platform behave similarly to the floor, the ratio between the floor's and the platform's frequency responses was taken. This is depicted in Fig. 4.17. We then smoothed the response by means of a Savitzky-Golay 3rd order filter. The compensation filter was then implemented in Max and used to process the stimuli to be used in the bouncing experiment. The stimuli low-pass filtered at 200 Hz and then equalized using a biquadratic filter implementing the compensation frequency response.

The intensity of the stimuli used during the experiment was adjusted to deliver a peak amplitude of 75 dB[10], measured at the platform using the accelerometer. This intensity level was judged to provide above threshold vibrations, while reducing the auditory feedback to a non-audible level for normal-hearing participants wearing ear muffs.

[10]Reference level at $10^{-6} m/s^2$ ($1 m/s^2$ corresponds to a 1 mV variation in the accelerometer output).

Ultimately, the platform proved to be a reliable yet portable experimental tool, capable of simulating a real-life floor-like response with adjustable intensity. The device was successfully used on the profoundly deaf and normal-hearing control subjects during the experiment's data acquisition phase.

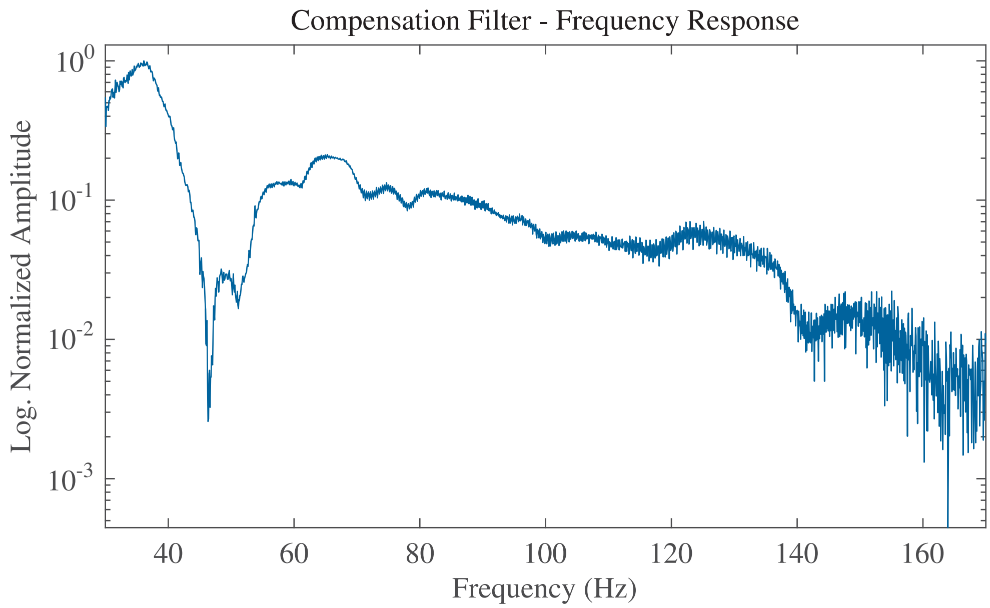


Figure 4.17: Amplitude response of the compensation filter used to equalized the stimulus used for the bouncing experiment. The filter was implemented in Max using a cascade of biquaratic filter object.

4.4 Conclusions

In this Chapter we have presented several applications of tactile translation using voice-coil actuators, in the context of: enhancing the simulation of the interaction with the haptic model of a musical instrument via a force feedback device; rendering the haptic behavior of an acoustic musical instrument; simulating the haptic behavior of a vibrating structure (i.e. a wooden floor) onto another one by means of frequency compensation techniques.

In the first application, we demonstrated that it is possible to improve the frequency content deliverable by a low-end force-feedback device, by a relatively simple and inexpensive modification of its hand effector. By comparing the response of the device with and without our modification, we show that the physical limitation's of the device's kinematic chain can be mitigated by a dual-channel approach.

The second experiment illustrates the use of frequency compensation techniques and haptic rendering of instrument vibration to perform a user-based study investigating the haptic behavior of the plucking of an instrument.

Lastly, we show an example of tactile synthesis by means of response modeling using frequency compensation techniques. A wooden platform is embedded with a shaker actuator and an offline compensation filter allows the reproduction on the platform of the vibrating behavior of a real wooden floor. The device was used successfully in an experiment investigating the perception of a musical beat through floor vibration.

Overall, in this Chapter we provided examples of tactile translation applications using voice coils actuators, and showed that this type of actuators can be proficiently used in the context of investigation, enhancement and simulation of the haptic response of several vibrating structures.

In the next Chapter we present several applications of tactile-augmented interfaces in the context of musical interaction and art installations, in which we mainly employed ERM actuators. We present several strategies to compose musically relevant tactile effects using the limited control space of these actuators, together with the technical challenges faced in the implementation of multi-actuator tactile-augmented devices.

Chapter 5

Tactile-Augmented Wearables for Music Performance and Media Installations

In this Chapter we describe the design and implementation of the hardware and software solutions used in the development of wearable devices augmented with vibrating motors, to be used in media installations and music performance. These augmented garments are embedded with ERM motors to convey localized and whole-body tactile effects. We present the technical challenges and design choices behind the hardware design of the system used to control the garments, as well as the synthesis and evaluation of tactile effects and icons to be delivered by these garments.

The first result is the implementation of the hardware infrastructure for a whole-body tactile augmented garment for *Ilinx*[1], a media installation in which haptic effects are presented as well as auditory and visual stimuli. A first exploration of the development of tactile effects to be delivered by the augmented garment is proposed together with the implementation of a library of haptic effects.

This approach is further developed and systematized in the second Section of this Chapter, in which we present the design and evaluation of tactile icons for expert musicians. These icons, developed for a tactile-augmented belt utilizing the technology developed for the *Ilinx* installation, represent the first step towards the development of a series of garments embedded with ERM actuators, and a vocabulary of tactile effects to be used in expert music performance. This work was completed in the context of *Musicking the Body Electric*, a four-year multidisciplinary project aimed at developing

[1] `http://phonomena.net/ilinx/`

a set of building blocks for the creation of a wearable score. This wearable score is intended for use in new works by composers and media artists.

5.1 The *"Ilinx"* Suit: A Tactile-Augmented Garment for a Multisensory Art Installation[2]

Ilinx is a multisensory art installation, exploring the interaction of vibration, sound and visuals, which was the result of a one-year, multidisciplinary project[3], bringing together haptic researchers, wearable designer, and media artists. A garment embedded with vibrating motors and a vocabulary of haptic effects were designed and assembled from scratch, and were subsequently integrated in the choreography of the art installation, which premiered in September 2014.

After briefly describing the installation, our focus will be on the design process and technical challenges behind the development of the haptic technology used in the suits. We then provide a description of the hardware and software used to control the garments and to define a basic vocabulary of haptic effects.

5.1.1 *Ilinx*[4]

Each of the Ilinx suits is composed of a jacket and two leggings, featuring six actuators around the waist, and 6 along each arm and leg for a total of 30 actuators. Participants also wore a semi-opaque visor, which was used to blur their sense of vision. The installation is conceived to host a maximum of four participants at the time. Visitors started their experience in a dressing room adjacent to the performance space, in which volunteers helped them wear the garments and the visor. Subsequently, the volunteers guided them into the performance space where the actual installation took place. Two

[2]This Section is based on *"Design and Implementation of a Whole-Body Haptic Suit for "Ilinx", a Multisensory Art Installation"* - M. Giordano, I. Hattwick, I. Franco, D. Egloff, E. Frid, V. Lamontagne, TeZ, C. Salter and M.M. Wanderley - Proceedings of SMC, 2015.

[3]Ilinx - Principal Investigators: Christopher Salter (Concordia University, Montreal) and Marcelo Wanderley (McGill University, Montreal) - Funded by the Canada Council for the Arts and the Natural Sciences and Engineering Research Council of Canada.

[4]The term ilinx was introduced by sociologist Roger Caillois and indicates an activity which causes a temporary perceptual disruption.

volunteers remained in the room to guide participants through the different phases of the installation.

The installation was divided into two sections. In the first section, participants entered the pitch-black room and were instructed to sit on a chair. The suits were then activated and produced a vibrating pulse effect, which was synchronized to a bell-like sound produced by quadraphonic speakers. The duration of this section was of approximately seven minutes, and new sonic and tactile material was progressively introduced throughout the section. The second section started with the appearance of faint lights, and at this point participants were instructed to stand and explore the environment while holding guiding ropes running across the room. More visual and sonic effects appeared and vibration patterns matching sound and light effects in the room were continuously delivered via the suit. The second session also lasted approximately seven minutes, after which participants were led outside the performance space and back into the dressing room to remove the visor and garments.

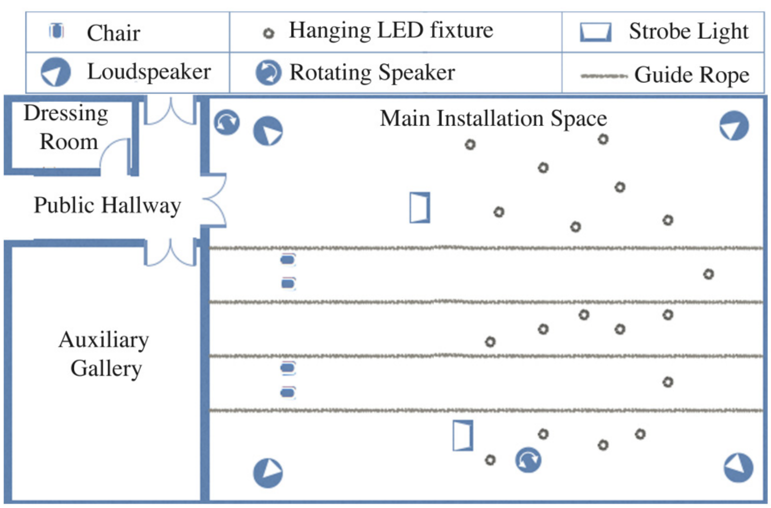


Figure 5.1: Diagram illustrating the installation space (courtesy of Ian Hattwick).

5.1.2 The Ilinx Garments

The augmented garments used in the installation were designed and assembled from scratch. From the early stages of the project, several key aspects were clear and guided our design choices throughout the development process, which spanned over several

Figure 5.2: Two participants during the second section of the installation (photo courtesy of I. Hattwick).

months:

- A total of six suits had to be functional and ready to be shipped to the TodaysArt Festival by September 2014 — a year after the project's start date;
- The installation would take place in an open space, requiring the suits to be wirelessly controlled and battery powered. Moreover, tens of actuators would be contained in each suit, requiring the choice of a type of actuator guaranteeing a suitable functionality/cost trade off;
- Hundreds of participants would wear the suits during the installation. This required the suits to be light and flexible but also robust; several suit sizes would have to be assembled, requiring solutions to guarantee a tight skin-actuator contact;
- The suits' software interface would have to feature an accessible control system so to allow the media artists to easily compose interesting tactile effects for the installation. Hardware and software solutions specifically tailored for these requirements would need to be developed.

5.1.2.1 Actuator Choice

In the first phase of the project we focused on the choice of the vibrating actuators to be embedded in the garments. From our early estimations, each suit could have contained up to 50 vibrating elements, which made ease of large-scale deployment, price, and size our primary concerns for choosing an actuator type.

We evaluated different kinds of actuators (see Chapter 3), including ERMs, LRAs, and voice-coil tactile transducers: voice-coils, while offering greater flexibility in terms of design of haptic effects, were not a viable option in terms of cost and and complexity of the electronic circuitry needed to drive them. LRAs offered the best power efficiency, but were excluded because of cost and limited vibration amplitude. Ultimately, we chose to utilize ERM motors (the VPM2 actuators presented in Chapter 3 and used in several other projects presented in this dissertation) for several key reasons: ERM motors are relatively inexpensive and readily available due to their widespread use; they require simple electronics to drive them and, given their small form factor, they can be easily configured in large arrays.

Moreover, we had previously conducted two perceptual tests of the ERM motors [Frid et al., 2014], to characterize their mechanical properties as perceived by a user. These tests helped us define perceptual detection thresholds as well as discrimination thresholds of the vibration produced by the ERM motor. The results obtained from this test allowed us to have a clearer picture of a user's perception of the ERMs' behavior, and hence enable us to design more meaningful tactile effects for the suits. The tests were conducted with the actuators placed on participants' backs. In this early phase of the project neither the final design of the suit nor the final arrangement of the actuators had been determined. Nonetheless, the suits would have most likely covered non-glabrous skin, making the back — which is mostly covered in non-glabrous skin — a suitable choice for investigating perceptual thresholds.

5.1.2.2 Perceptual Characterization of Actuator Produced Vibrations[5]

The two experiments were conducted on the ERM motors driven by a ULN2803A IC unit, the same IC characterized in Chapter 3, and were aimed at investigating vibrotactile absolute threshold (Experiment 1) and vibrotactile differential threshold (Experiment 2). With Experiment 1 we wanted to identify the minimum intensity required for a user to perceive the ERM as vibrating. Experiment 2 was conducted with the aim of characterizing the minimal intensity difference for two subsequent stimuli to be reliably perceived as being different. Eight subjects (4 men and 4 women, 21 to 31 years old) took part to Experiment 1 and 10 subjects (5 men and 5 women, 21 to 31 years old) in Experiment 2.

Two ERM motors driven via a PWM signal from an Arduino board were placed on the back of the subjects, using velcro band. The actuators were placed symmetrically about the spine and participants wore the display directly on the skin. A Max control environment was programmed using the Firmata protocol[6] to communicate between the Max computer and the Arduino board.

Participants were also asked to wear headphones producing a level of pink noise sufficient to mask actuators' noise at the highest dutycycle level. This was done in order to prevent possible bias from auditory cues.

Experiment 1: Vibrotactile Absolute Threshold The aim of this experiment was to identify the perceptual threshold of vibration for the ERM motors, i.e. the PWM dutycycle value at which participants would report to start feeling vibration from the motors. Five discrete PWM values (from 10% to 50%) were tested; the choice of these values was based on the assumption that vibrations above 50% dutycycle would be supra-threshold.

Thirty stimuli were presented in total, with each intensity level repeated six times and presented in a randomized order. Stimuli length was set to 500 ms. After five stimuli presented to the left actuator, the next set of five stimuli would be presented to the right actuator in order to compensate for adaptation effect [Verrillo, 1992]. A pause

[5]This Section is based on *"Physical and Perceptual Characterization of a Tactile Display for a Live-Electronics Notification System"* - E. Frid, M. Giordano, M. Schumacher and M. M. Wanderley - In Proceedings of the ICMC and SMC, 2014.

[6]`https://www.arduino.cc/en/Reference/Firmata`

of the same length of the five-stimulus set was introduced to recover from the sensory magnitude loss [van Erp, 2002].

Participants were asked to press the space-bar of an external keyboard every time he or she could perceive a stimulus. The proportion of detected stimuli was annotated for each stimulus intensity. The absolute threshold was defined as the point where the proportion of detected stimuli was above 50 %.

Results Stimuli would be considered above threshold if participants detected them more than 50% of the times they were presented. Stimuli with a dutycycle of 10% were detected only 4.2 % of the times, and can hence be considered below threshold. Stimuli from 20% to 50% dutycycle were all above threshold.

Experiment 2: Vibrotactile Differential Threshold With the vibrotactile differential threshold experiment we aimed at characterizing the minimal change in the 10-step dutycycle scale at which a difference between supra-threshold stimuli can be robustly detected (i.e. more than 80% of the presented times).

A set of pairs of stimuli was designed, consisting of a first 500 ms long actuation, followed by a pause of randomized length (between 750ms and 1500 ms), and then by a second stimulus of 500 ms. All combinations of discrete, supra-threshold intensities were testes (from 20% to 100%), producing a set of 81 pairs, of which 9 featured the same intensity for the first and the second actuation, and 72 featured different intensity levels.

To compensate for adaptation effects, five pairs were presented on the left actuator, followed by a 15-second pause and by another set of 5 pairs on the right actuator.

Participants were instructed to enter their response on an external computer keyboard, on which two keys were labeled “same” or “different”. Participants had 4.5 seconds to answer after the end of the second stimulus in the pair. If no response had been entered after 4.5 seconds, the answer would be automatically recorded as “same”, since we assumed that a longer decision time would suggest that the stimuli felt similar.

Results Results for this experiment show that in order to guarantee a robust discrimination (i.e., at least 80%) between subsequent stimuli, their intensity levels need to differ (Δ) from 32 to 53% (see Table 5.1). It has been reported that a difference of at least 20-30% in amplitude is sufficient for discrimination between vibrotactile stimuli at different intensities [Choi and Kuchenbecker, 2013]. Given the requirement of 80% discrimination rate set in our experiment though, it is not surprising that the range of intensity difference we found is higher than what previously reported.

It is also worth noticing that our test showed that the order of presentation of the two stimuli (i.e., stronger followed by weaker of vice-versa) has no statistically significant effect.

PWM_0 **(%)**	20	30	40	50	60	70	80	90	100
$\Delta(\%)$	32	35	37	40	43	45	48	51	53
%	39.90	43.26	46.63	49.99	53.35	56.72	60.09	63.45	66.81

Table 5.1: Required duty cycle differences (Δ) necessary to obtain robust discrimination (i.e. judged as different at least 80% of the times) between vibrotactile stimuli, with a start value of PWM_0. The difference in percentage (%) is calculated with respect to an 80% total range (100% - 20%, 20% being the perceptual threshold).

Overall, these results show that the ERM motors could provide users with supra-threshold vibrations in most of their range. All the stimuli above 20% dutycycle were correctly identified. In terms of amplitude levels, the tests allowed us to determine that, if reliable discrimination of vibration amplitude was to be a parameter in our tactile effects, the motors could provide us with three discrete intensity steps (see table 5.1).

5.1.2.3 Actuator Positioning Tests

The perpetual tests we presented gave us indications about the temporal properties of the vibration produced by the ERM motors, as perceived by users. Our next step was to investigate the effects of spatial distribution of the motors on the body, in terms of distance and pattern configurations on the limbs.

Early ideas of the wearable prototype were informed by previous work on vibrotactile augmented garments [Gunther and O'Modhrain, 2003; van Erp et al., 2005; Lemmens et al., 2009] and by modular designs of vibrotactile systems [Knutzen et al., 2014; Egloff et al., 2011]. The first wearable prototype consisted of ERMs mounted on a 3M Dual Lock velcro strip (see Fig. 5.3). Prototyping with the velcro tape proved to be useful for heuristically determining distances between individual actuators and receptive fields of the body, as the motors could be easily rearranged along the tape. During this early test phase, several actuator placements were tested in order to determine the optimal distance between two actuators, based on the experimental data reported in Fig. 2.3. Actuators were placed close together at first and then rearranged to increase the distance between them until two distinct vibrotactile sensations could be felt. This allowed us to determine, for instance, a 5 cm optimal distance on the arm for which vibrations coming from different actuators would consistently be associated to different loci. These results are consistent with results found in the literature [Cholewiak, Collins, and Brill, 2001], as reported in Chapter 2.

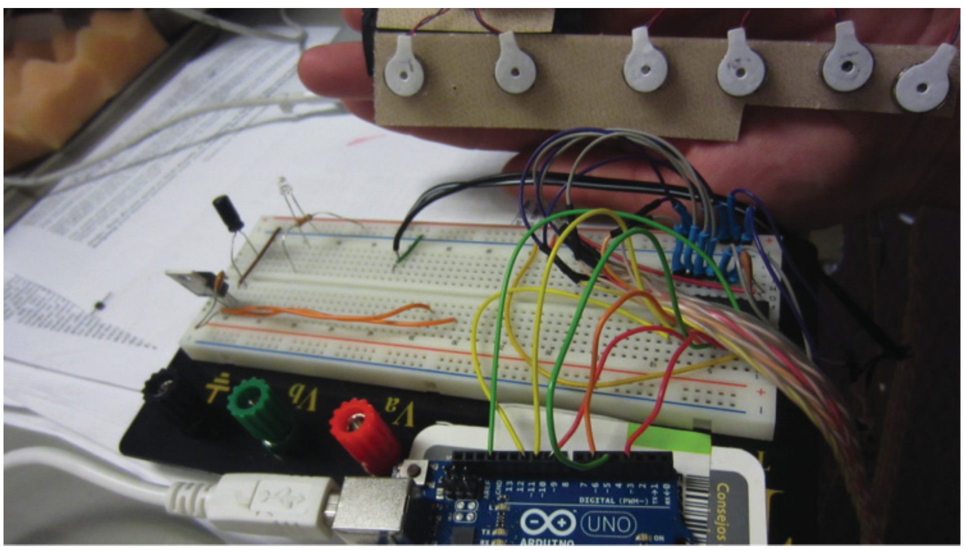


Figure 5.3: Early prototype using a Dual-Lock Velcro strip.

The actuator strip proved to be a useful tool to explore the effect of vibration patterns applied to several parts of the body. We were interested in determining if the illusion of continuous motion along a limb could be elicited by producing sequences of vibrations, and what the temporal properties of these vibrations should be in order for this effect to be convincing. We applied the actuators to different body parts (such as legs, stomach, back, inner and outer arms, neck and torso) in order to determine viable actuator placements. As mentioned, parallel arrays of actuators on the back had been considered in early tests, but the most salient sensations were found to be when the strip was either placed in a circular shape around the waist, longitudinally along the outside of the leg, or twirled around the leg (these findings inspired the early sketching

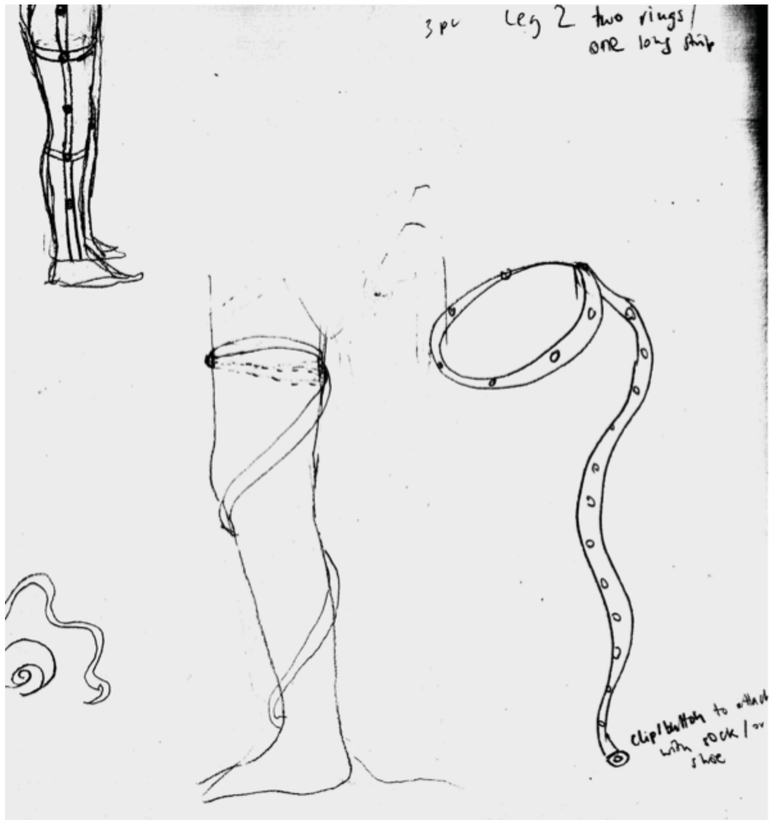


Figure 5.4: Sketches of possible actuator arrangement using detachable fabric strips (drawings by Deborah Egloff).

shown in Fig. 5.4). In terms of temporal properties, longer overlaps between contiguous motor activation would enhance the sense of continuity at slower speeds, while at faster speeds little to no overlap seemed to be required. Overall, these configurations were all equally satisfying in terms of creating the illusion of continuous motion [Geldard and Sherrick, 1972].

Ultimately, we decided to implement a suit comprising five modules of six actuators each. These would be disposed on a longitudinal array for arms and legs, and circularly around the waist. This decision was the result of the exploratory tests using the actuator strip as well as practical considerations dictated by the project's tight schedule. The tests showed this actuator placement could at the same time produce spatially-distinct individual actuations, and also elicit the illusion of continuous motion along the body, using the previously mentioned temporal-overlapping techniques.

A longitudinal design would, at the same time, provide the wearable designers and seamstresses with an easier task in terms of the manufacturing of the garments.

5.1.2.4 Garment

After several iterations, six garments were designed and manufactured by a team led by Valérie Lamontagne[7], consisting of two leggings and a single jacket with sleeves. The garments were available in three different sizes (small, medium and large) so to be able to accommodate for different body sizes of the visitors taking part to the installation.

Velcro straps were used to secure the sleeves to the arm in three locations and the leggings to the legs in four locations. In addition, a wider velcro strap was used to secure the main body of the jacket to the torso. The open sleeves and leggings came with the advantage of being easy to put on and take off while holding actuators tightly to the body. Fig. 5.5 shows the final prototype of the suit, while Fig. 5.6 shows the final version of the garment which was used for the installation at the TodaysArt festival.

5.1.3 Hardware and Control System

5.1.3.1 Hardware

The electronics for each garment consist of five circuit boards — one for each suit segment (two arms, two legs, and torso) — and a single central node unit. Each segment's circuit board features a power regulator, a movement sensor consisting of 3-axis accelerometer, gyroscope, and magnetometer, and an Arduino-compatible microcontroller for generating the control signals to the motors. These signals are transmitted to a series of three LB1837M3 drivers which can control up to six motors (2 motors per driver). An RJ45 connector at the back is used to connect the board to the central unit (see Fig. 5.7). The boards had 12 large holes to which conductive thread was embroidered in order to deliver power to the ERMs. This embroidering also served to securely attach the PCB to the garment. The movement sensor integrated in the boards could be used to collect information about each module's movement and relative orientation. This data was not used by the media artists in the final choreography of the installation.

[7] `http://www.valerielamontagne.com/`

Figure 5.5: The final prototype of the garment designed by V. Lamontagne's team. The actuators are clearly visible on the two leg modules and on the jacket (sleeves and waist). The green labels show the name of the modules as they are referred to in Sec. 5.1.3.3.

Figure 5.6: The final version of the garment wore by a participant at the TodaysArt festival (photo courtesy of I. Hattwick).

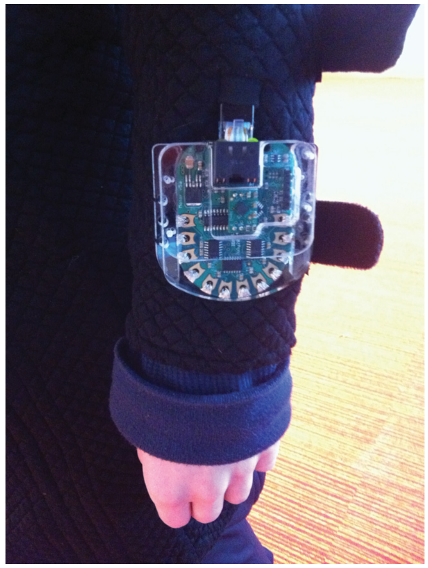


Figure 5.7: Detailed of the driver board visible on the garment's sleeve (photo courtesy of I. Hattwick).

The central node, depicted in Fig. 5.8, consists of a BeagleBone Black (BBB) mini-computer running Linux and a usb WiFi dongle. The BBB is responsible for transmitting and receiving OSC messages over WiFi and routing incoming messages to the appropriate motor driver board. A custom board featuring 5 RJ45 connectors interfaces the motor driver boards to the central unit.

One key concern of the costume designers was to maximize the garments' flexibility. To achieve this goal, the Ethernet cables connecting the driver boards to the BBB had their external covers removed, and conductive thread was used to connect the motors to the driver boards. It was also necessary to find a way to securely attach the motors to the garment which would also provide for a close fit between the motors and the body when the garment was worn. A 3D-printed housing for the motor (shown in Fig. 5.9), which contained three circular mounting points for sewing to the garment, served these functions. The wires connecting to the motor were soldered to ring terminals which fit into the housing, and conductive thread was embroidered around both the holes in the housing and the ring terminal. This allowed the seamstresses to fasten the housing to the garment and make the electrical connection between the motor and the conductive thread.

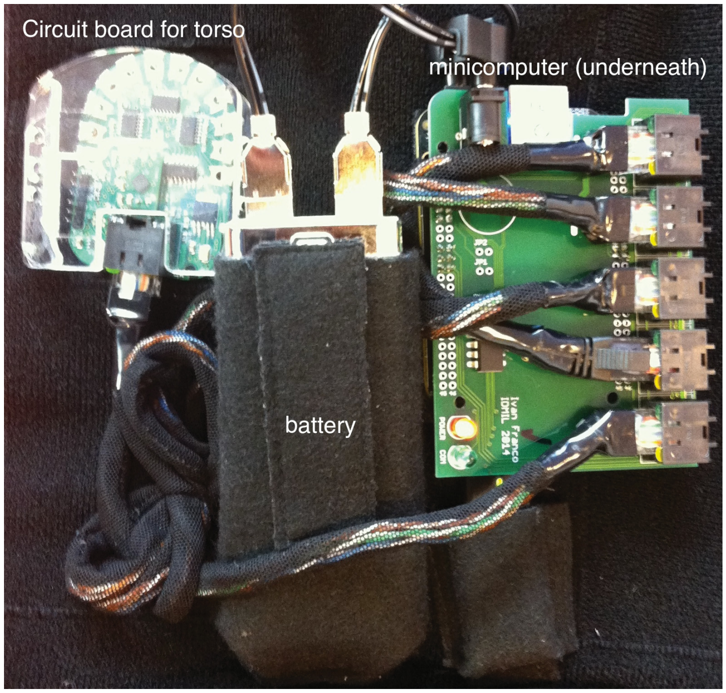


Figure 5.8: A driver board (left side, PCB design by I. Hattwick) connected to the custom cape (PCB design by Ivan Franco) for the Beaglebone Black (BBB) central unit (underneath).

Figure 5.9: 3D-printed housing for connecting the motors to the garments (3D design by I. Hattwick).

5.1.3.2 System Architecture

The Beaglebone Black (BBB) is a popular single-board computer with a 1GHz ARM® Cortex-A8 processor and runs a regular Linux distribution. In our system, the BBB controls each of the individual driver boards through a custom PCB board (or cape), which implements a standard Serial Peripheral Interface (SPI) bus. This SPI custom board is mounted directly on the BBB board and provides connectivity and power to each of the five driver boards through standard Ethernet connectors. Power is provided by a battery with two independent outputs, one plugged to the BBB and another to the SPI board. The eight separate wires in a standard Ethernet cable provided us with the perfect solution to transmit data and power at the same time.

The BBB is connected to a local wireless network through a small WiFi USB dongle, and each garment can be individually addressed by its IP address on the local network. We developed a messaging system based on the Open Sound Control protocol (OSC), which was used to control each suit. A Python implementation of an OSC server and message parser continuously running on the BBB is responsible of routing individual messages to the correct driver board via the SPI bus. Additionally, this system can be monitored and controlled through a *ssh* connection via a standard Unix shell, through which it is possible to monitor the internal state of the OSC message parser as well as the lower level communication to each driver board via the SPI bus.

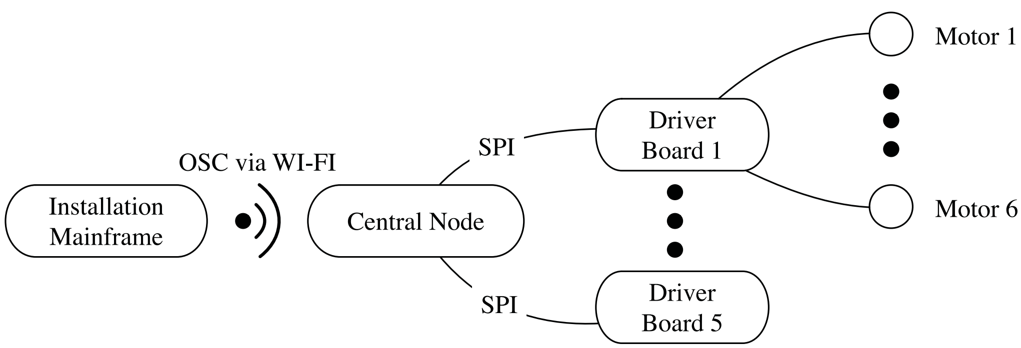


Figure 5.10: Schematization of the signal flow from the computer generating the OSC message to the target moror.

5.1.3.3 Message Namespace

The messaging system implements a OSC namespace in which driver boards are named after the suit module they are controlling (see Fig. 5.5):

- /ar: Right Arm
- /al: Left Arm
- /tf: Torso
- /ll: Left Leg

- /lr: Right Leg

Individual motors are addressed through a continuous value from 0 to 1, which represents the motor's location on the body segment. The rest of the message describes the actuator's activation pattern by means of temporal properties, which we call *haptic envelope* messages. These haptic envelopes are the building blocks of the tactile effects we will describe in Section 5.1.4.

The attack time, sustain time, and release time are expressed in milliseconds, while the sustain intensity level, from 0 to 1, represents the dutycyle of the PWM signal delivered to the motors. For instance, the following message would be sent to the target suit's IP address to activate the second actuator on the left leg module (`/ll`). The motor would take 250 ms (attack time) to reach a vibration intensity of 0.7, it would then remain at this intensity level for 500 ms (sustain time) and then stop in 250 ms (release time).

```
/ll 0.4 250 500 0.7 250
```

This protocol allows for the generation of the control signals for the motors to be located on each driver board while the definition of higher-level haptic effects takes place on the external computer running the control software generating the OSC signals. While it could have been possible to define and embed higher-level effects directly on the hardware system, this simple and effective control protocol allows users to design their own effects and control the system with many different types of software. For the Ilinix installation a control environment programmed in *Max* featured an haptic sequencer, which was integrated into the performance control mainframe. This allowed for an easy and accurate synchronization between haptics and audiovisual events happening throughout the installation, which were also controlled though a Max-based software.

5.1.4 Haptic Effects

Given the flexibility of the control space designed for the suits the media-artists composing the installation's choreography could freely implement the tactile synthesis of their own haptic effects. We nonetheless provided them with a small library of pre-programmed effects, which they could directly recall from the Max control interface.

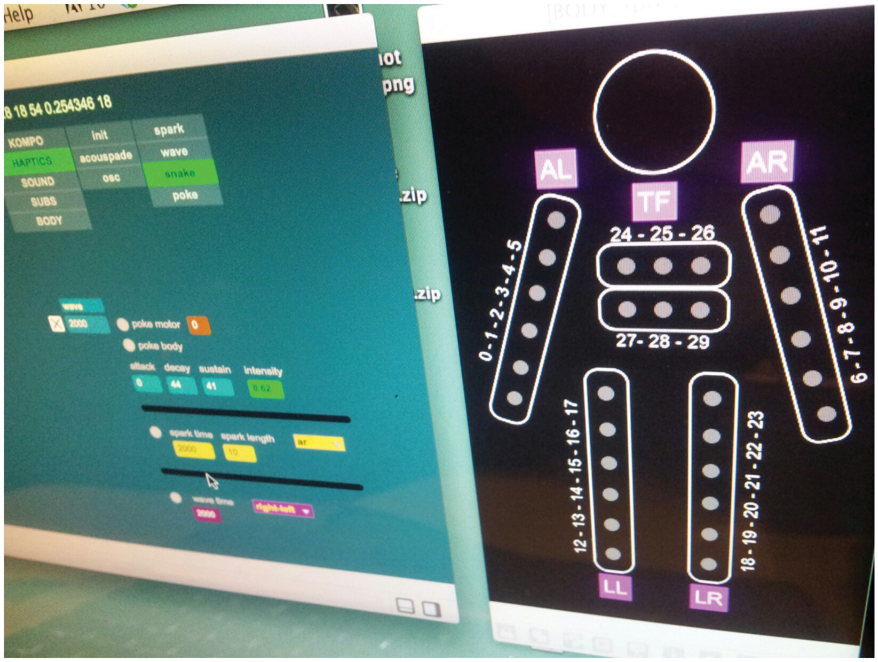


Figure 5.11: The Max control environment developed by TeZ (Maurizio Martinucci). The artist could recall the pre-programmed effects we designed from a drop-down menu, and see the actuators' activation pattern on a simulation of the target suit (visible as a stick-figure on the right side).

We identified two main categories of effects which could be easily implemented on the suits — namely, discrete and continuous effects — and developed an arbitrary number of six haptic effects in total, using the Max sequencer we programmed. The discrete effects are the *Pokes*, *Buzzes* and *Sparkles*. The first two effects are achieved through a simple activation of one or more target motors. A *Poke* is implemented sending a sharper envelope message, while a *Buzz*-envelope has longer attack and decay times. The *Sparkles* effect consists of random activation of the motors, which can happen all over the body, or can be limited to one specified target limb. A haptic envelope can be specified to determine the duration and intensity of each *Sparkle*. Overall, discrete effects are effects whose single instances are perceived as occurring at a single location on the body.

Continuous effects, on the other hand, use a combination of motors to create sensations that are perceived as moving on the body, and they rely on a precise pattern of actuation, as well as on haptic envelopes overlapping between several contiguous motors. One example is the *Snake* effect, which requires the definition of a starting and ending point, duration, intensity and overlap factor (i.e. overlap between subsequent motor activations). An illustration of the effect is depicted in Fig. 5.12. A *Wave* effect reproduces the effect of a wave traveling horizontally or vertically across the body by sequential, overlapping activation of contiguous motors on a several body segment. The *Spin* effect produces instead the sensation of a continuous circular motion around the waist, for which speed and intensity can be selected.

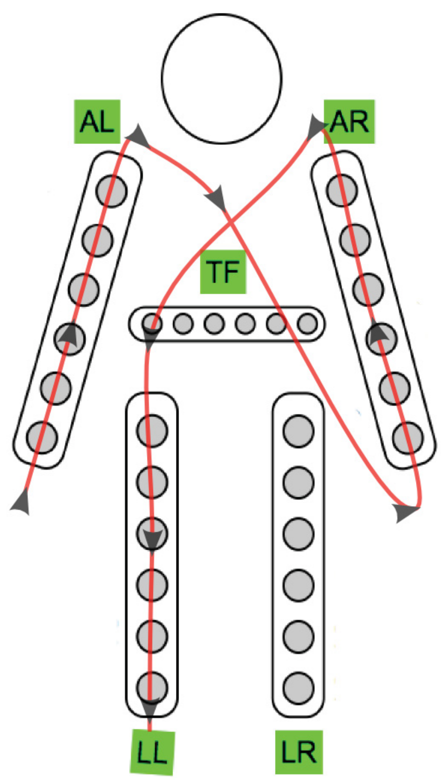


Figure 5.12: The representation of the garment in *Max*. The red path shows the actuation pattern of the *Snake* effect: a wave of vibrations traveling along the limbs, following a pre-programmed order.

These effects provided the installation designers with building blocks from which they could develop their own effects by, for instance, a combination of several continuous and discrete effects.

5.1.5 Feedback from Participants to the TodaysArt Festival

Six unstructured interviews involving visitors of the TodaysArt Festival were conducted after the installation. From the feedback we collected we could extrapolate the following main points about participants' perception of the suits and the haptic effects:

- Participants experienced different degrees of satisfaction concerning the tightness of the suit, especially for the actuators positioned around the waist. Some of them found it too loose, while others judged the tightness to be good enough to guarantee constant actuator-skin contact.
- Participants consistently underestimated the number of actuators embedded in the suit (responses varied from 10 to 20);
- Vibrations were felt more clearly in the first section of the piece. In the second section, when participants were standing and walking in an environment full of rich auditory and visual stimuli, the focus shifted from the tactile sense to the other senses (in accordance with results presented in Chapter 2).

Overall, participant enjoyed the installation, judging it surprising and engaging. They agreed that, in the body parts for which a sufficient level of tightness was reached, vibration effects could clearly be perceived. They perceived haptic effects such as the *Snake* as continuous vibrations traveling across the body, which suggests that the haptic effects we designed were accurately rendered through the suits.

5.1.6 Remarks

Given the time constraints due to the needs of the artistic project, the Ilinx suit could only be partially exploited and the effectiveness of the tactile effects we designed could not be thoroughly evaluated. Nonetheless, the hardware and software developed in this project proved to be crucial in the realization of other projects that we will present in the following Sections as well as in the next Chapter. The robustness of the system architecture and the flexibility of the haptic envelope messages allowed us to leverage the results we just described to continue the development of new wearable haptic enabled systems.

5.2 Towards a Wearable Score: Development and Evaluation of Tactile Icons for Music Performance

In this Section we present the results achieved in the more systematical investigation of the synthesis of haptic effects delivered via tactile augmented garments. The hardware and software developed for the Ilinx suits, as well as our investigation into the design of whole-body tactile effects, provided us with the necessary tools to pursue our research.

Our work was conducted in the context of *"Musicking the Body Electric"*[8], a four-year, multidisciplinary project involving researchers from the fields of haptics, music technology, music education, composition and wearable electronics. This project provided us with the perfect conditions to continue our work on the synthesis of tactile effects, but this time in the context of musical interaction.

The ultimate goal of the project is to develop tactile-augmented suits and a language of tactons [Brown, Brewster, et al., 2005], to be used as building blocks for a *wearable score* system. The language will allow composers to convey musical information via tactile stimulation in the context of a music performance in which musicians are free to walk in the performance space. The augmented garments will ultimately be able to sense the location of the musicians in the performance space and also the position of musicians relative to one another. This, for instance, would allow each of the suits to be aware of the proximity of other musicians in the room and cue them to play a given section of the piece by delivering the corresponding tactile icon.

The work we present is the result of the first year of tests conducted on the Ilinx suit, and on the first two specialized garments produced for the project: an augmented belt embedded with six vibrating actuators and an elastic band embedded with a single actuator.

5.2.1 Preliminary Explorations

Since the early phases of the project, we collaborated with Audrey-Kristel Barbeau, a research assistant from the McGill University music education area who participated

[8]Musicking the Body Electric - Principal investigators: Sandeep Bhagwati (Matralab, Concodia University, Montreal), Marcelo Wanderley (McGill University, Montreal), Isabelle Cossette (MPBL, McGill Univesrity), Joanna Berzowska (XS Labs, Concordia University) - Funded by the Social Sciences and Humanities Research Council of Canada.

in the tactile effects design and testing. In the first exploration phase, the garments of Ilinx suit were used to test the effectiveness of mappings between vibrations and musical tasks. Several approaches were investigated: the leg modules, comprised of six actuators longitudinally disposed, were used to convey either localized *Buzzes* or continuous *Waves* (see Section 5.1.4). The buzzing of a single actuator was mapped to a note on a pentatonic scale (only five of six actuators were used in this configuration), while an ascending or descending wave was mapped respectively to an ascending or descending scale. The research assistant performed the given tasks on a trumpet, and provided immediate feedback on perceived distinguishability and properties of the haptic envelopes used for the effects. Only qualitative feedback was collected in this preliminary phase and we did not conduct any data collection on the effects' recognition rates.

The Ilinx jacket was also tested in this phase. Similar strategies as the ones presented for the legs were implemented for the arms, and a preliminary mapping of the actuators around the waist was also tested. The research assistant reported not enough sensitivity to reliably identify the icons, especially on the upper arms, while the waist presented the same tightness problems reported by some participants to the TodaysArt festival (see Section 5.1.5). This prevented a consistent skin-actuator contact, hence making some tactile effects go undetected. Nonetheless, the circular arrangement of the actuators around hips or waist seemed to be most promising in terms of flexibility for the synthesis of tactile icons. Moreover, as mentioned in Chapter 2, several successful works exist in the literature using tactile augmented belts for navigational tasks [Tsukada and Yasumura, 2004; van Erp et al., 2005], suggesting that this part of the body could offer a sufficient spatial resolution.

Overall, this exploratory phase suggested that meaningful mappings between tactile icons and musical tasks could be established. The preliminary testing also revealed that the *one size fits all* nature of the Ilinx suit was not adequate for the necessary level of tightness required: customized, per-performer garments had to be produced to systematically test the distinguishability of the tactile effects.

5.2.2 Symbolic and Musical Tactons: Design and Evaluation

The wearable designers involved in the project (Joanna Berzowska and Alex Bachmayer, XS Labs, Concordia University) produced the first specialized garment for us to test: a tactile augmented belt featuring 6 equally spaced ERM actuators. The prototype belt, visible in Fig. 5.13, was custom-tailored to perfectly fit A.-K. Barbeau. The choice of a belt as the first garment to be designed, was guided by several reasons: as we mentioned, the placement of the actuators on a circle around the user's waist allowed for more flexibility in terms of tactile effects design; more practically, a belt provides an easier fit compared to leggings or sleeves for instance.

Figure 5.13: The augmented belt embedded with 6 Vibrating actuators (garment design and manufacturing J. Berzowska and A. Bachmayer — XS Labs, Concordia University).

We provided the wearable designers with electronics we developed for the Ilinx suit, presented in Section 5.1. This allowed us to keep controlling the actuators by means of haptic envelope messages formatted using the OSC namespace described in Section 5.1.3.3.

A second garment was also introduced, consisting of a single actuator mounted on an adjustable elastic band, which could easily be worn on body parts such as wrist, upper arm or ankle.

In this phase, our approach consisted in designing two sets of icons, to be produced respectively by the belt and the augmented elastic band. The former would be used to convey *symbolic* tactons, i.e. abstract patterns that musicians would need to learn and associate to specific musical elements, for instance sections of a score, chords etc. The latter would deliver instead *musical* tactons, i.e. tactons which carry a unique musical meaning, attached to the temporal properties of the tacton itself.

5.2.2.1 Symbolic Tactons

We identified three different dimensions defining the icon design space associated with the six-actuator belt:

- A spatial dimension, which is associated with the definition of geometrical patterns on the hexagon schematizing the disposition of the six actuators around the waist (see Fig. 5.15);
- A global temporal dimension of the icon. Once the geometrical pattern of the tacton has been defined, the temporal order or sequence in which the actuators are activated can shape the global perception of the tactile effect;
- An individual temporal dimension, which pertains to the properties of the haptic envelope controlling each individual actuator.

For the design of the symbolic icons we applied a heuristic approach: we defined several geometric patterns which we hypothesized would feature unique characteristics, making them easily distinguishable from one another; we then implemented these patterns, together with preliminary global and individual temporal properties, on a Max-based tactile sequencer we programmed to control the belt; the research assistant would then test the icons and provide immediate feedback to allow us to proceed to another iteration of the design process.

This process lasted over several weeks, after which we finalized a set of ten icons, depicted in Fig. 5.15. Each of the icons consists of two repetitions of the same pattern which are separated by a fixed time interval. The icons have a total duration which varies from 1500 ms to 2700 ms. For the individual temporal properties, we chose a fixed haptic envelope for all the actuations which features 50 ms of attack, 150 ms of sustain at maximum intensity and no release time (see Fig. 5.14). We decided to keep the haptic envelope parameters fixed for this initial phase of the project, to facilitate the icons' learning phase. The icons were proposed to the two undergraduate students from Concordia University, who took part to the evaluation sessions.

5.2.2.2 Musical Tactons

The symbolic tactons we designed for the belt do not carry any musical or other meaning per se, and need to be learned by the performers to be proficiently used to convey musical information. From a composer's point of view these icons can be mapped to

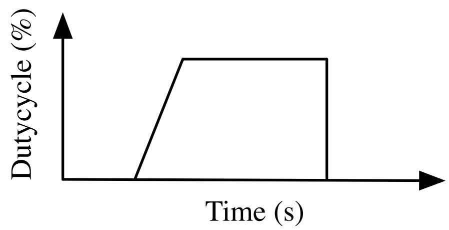


Figure 5.14: The haptic envelopes of each individual actuation composing the icons: 50 ms attack time to 100% dutycycle, 150 ms sustain and no release time.

several musical functions, such as chords, or sections of a piece, and these mappings also need to be mastered by musicians to be correctly interpreted.

The implementation of the musical tactons we developed for the single actuator attached to the elastic band followed the opposite approach, which started by determining the set of musical information this actuator would deliver. From the experience we gathered in our previous work, we hypothesized that a single-actuator configuration could be used to provide tempo cues, as well as information about articulation and dynamics.

Using the heuristic approach based on iterative feedback from our collaborator, we designed a set of four musical tactons respectively associated with *crescendo* (5.16a), *decrescendo* (5.16b), *staccato* (5.16c) and *legato* (5.16d). These icons contained a musical meaning attached to the temporal properties of the icon itself and would ideally require a minimal effort to be correctly interpreted.

5.2.2.3 Preliminary Evaluation

We conducted a preliminary evaluation of both symbolic and musical icons' design. This evaluation was conducted with the collaboration of a saxophone player (performer one) and a guitar player (performer two), both undergraduate music students at Concordia University who performed a series of musical tasks we associated to each of the icons. It was important for us to evaluate the learnability and recognition rate of the icons in the context of music performance in order to establish if musicians actively engaged in a musical task could reliably recognize and respond to the given icons.

We performed two testing sessions, 2 weeks apart, in which the musicians had 20

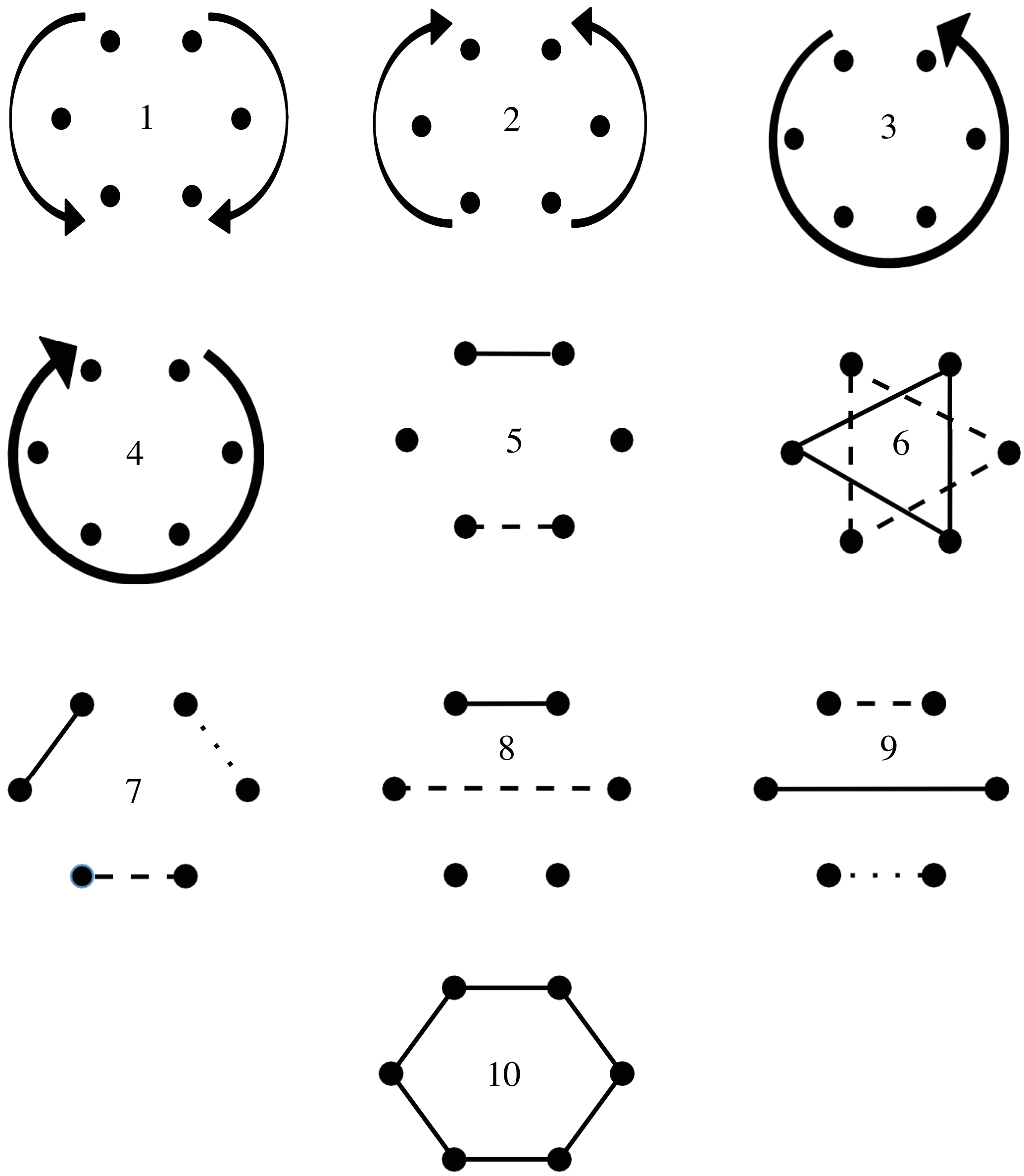
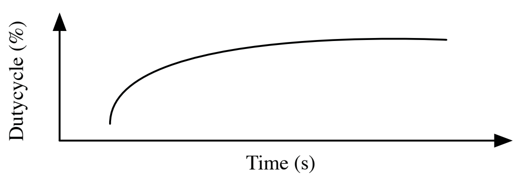
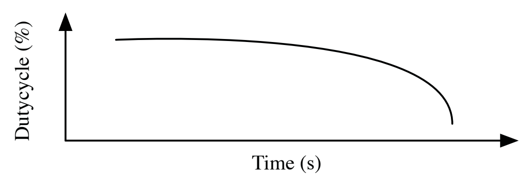


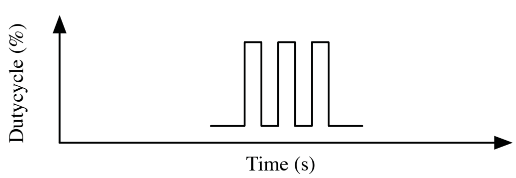
Figure 5.15: The final set of ten symbolic icons developed for the belt (diagram courtesy of A.-K. Barbeau). Each black dot represents one actuator. The hexagon shapes represent the actuators disposed around a user's waist, with the top two actuators corresponding to the person's front.
Icons 1 to 4 feature a sequence of actuations which follow the direction indicated by the arrows. For icons 5 to 10, connected dots represent simultaneous activation of the corresponding actuators, with solid lines happening first, followed by dashed and then dotted lines. Each actuation lasts 200 ms, as per haptic envelope definition, and for each icon the pattern is repeated twice with a 300 ms interval between repetitions.



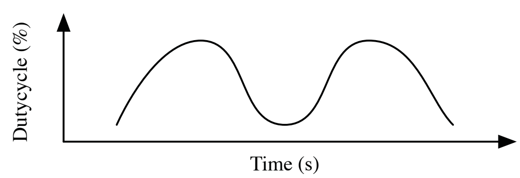
(a) The crescendo icon is achieved by means of exponentially increasing the dutycycle from 20% (perceptual threshold) to 100% over 2000 ms.



(b) The envelope for the decrescendo icon goes from 100% to 20% dutycycle over 2000 ms, by using a negative exponential function.



(c) The staccato icon is obtained by presenting three, 100 ms long vibrations at 100% dutycycle, with a 100 ms interval between each peak.



(d) The legato icon features 2 scaled sine waves going from 20% to 100% over 1000 ms.

Figure 5.16: Schematization of the envelopes of the four musical tactons we developed, to be delivered by the single-actuator.

minutes per session to familiarize themselves with the icons. Subsequently, they were asked to perform a recognition task, in which they had to experience a series of tactons and verbally report the name or number of the tacton they thought they had perceived (task 1). Afterwards, the musicians were given a score, as the one depicted in Fig. 5.17, and asked to perform the melody associated to the perceived icons (task 2). The melodies were composed so to be easy to sight-read and perform. In the first session only symbolic icons were tested, while in the second session we tested both symbolic and musical icons. Their performance was audio-recorded and subsequently analyzed to determine their recognition rates of the tactile icons in both sessions.

Session one We performed two repetitions, 10 minutes apart, of task 1. The results are depicted in Fig 5.18a and show the average recognition rate of twenty randomly ordered icons, for each of the two repetitions. Already for the first trial, the musicians reached respectively 86% and 77% of correct answer, both improving their performance in the second repetition to 88%.

Subsequently, we provided the musicians with the score in Fig. 5.17 and repeated the recognition task, this time asking them to play the melody corresponding to the perceived icon. The musicians were free to play at the tempo they desired. Fifteen randomly ordered icons were tested, and a new icon would be delivered via the belt while the musician was playing the half-note ending the previous melody. Task 2 was repeated three times, 10 minutes apart, and the results are depicted in Fig. 5.18b. The performers reached respectively a 92% and 79% recognition rate for the first trial, 92% and 86% for the second trial, and 88% and 71% for the last trial.

Session two Session two took place two weeks after session one, and for this session we tested both symbolic and musical tactons. Following the previously described protocol we performed task 1 first, whose results are depicted in Fig. 5.19a.

For the task 2, the musicians wore the belt, and the single actuator elastic band on their left upper arm. For this task, a symbolic icon would be delivered via the belt, followed by a musical icon from the single actuator. The musicians were asked to play the corresponding melody following either the articulation or the dynamics indicated by the musical tacton. Results are shown in Fig. 5.19b. For the symbolic icons, the first performer reached a recognition rate of 87% in the first trial, 86% in the second, 70%

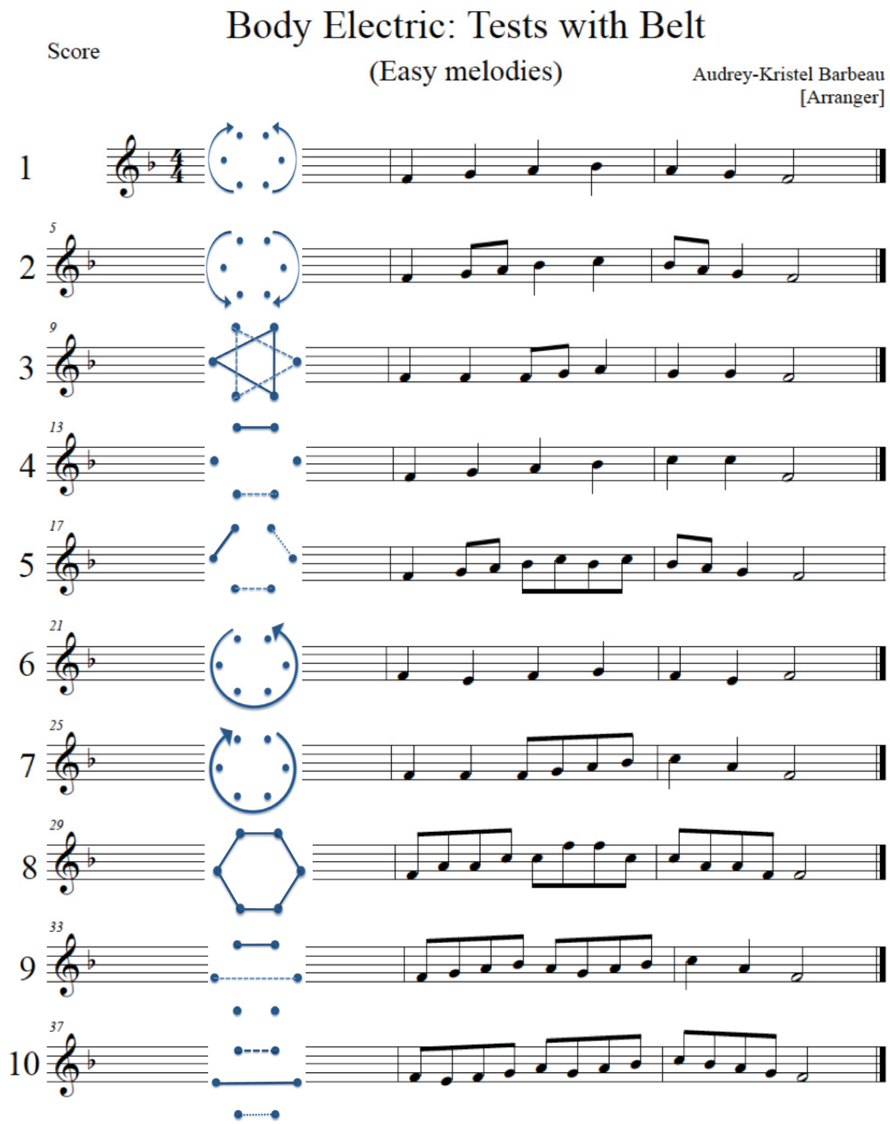
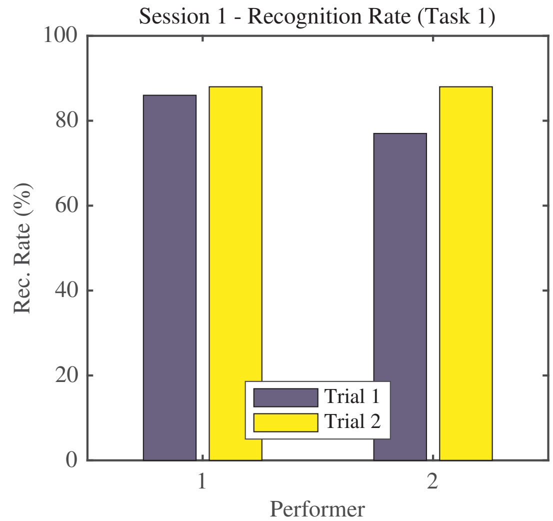
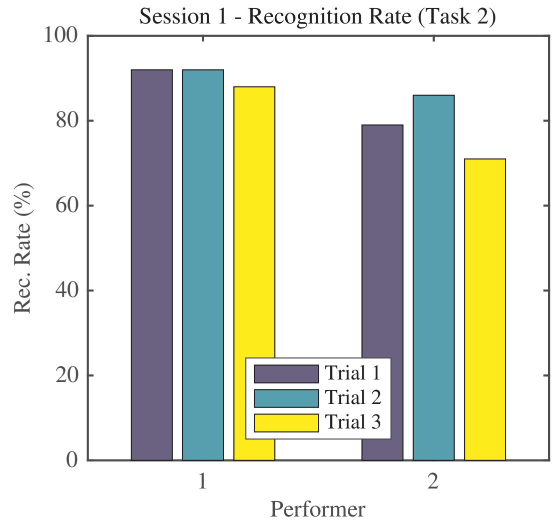


Figure 5.17: The set of 10 simple melodies, composed by A.-K. Barbeau, and associated to the ten symbolic icons. The performer would feel one of the icons on the augmented belt and perform the corresponding melody.



(a) Task 1 - Verbally report perceived icon.



(b) Task 2 - Play melody corresponding to the perceived icon as indicated on the score in Fig. 5.17.

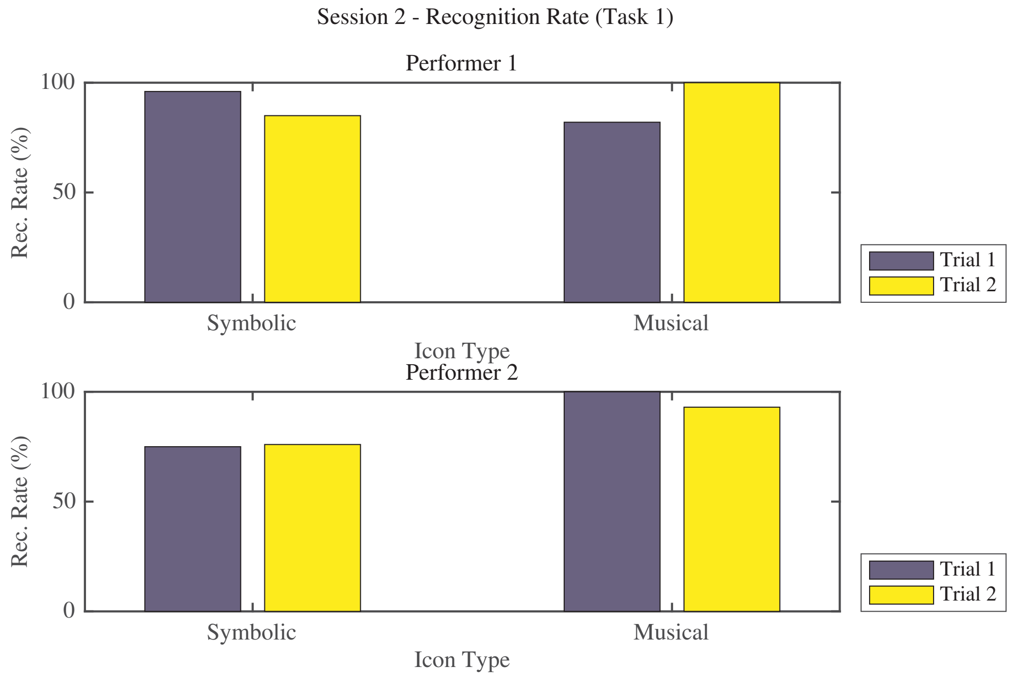
Figure 5.18: Recognition rates for Session 1 for both Task 1 and Task 2. Recognition rate are consistently around 80% for both participants.

and 78% in the third and fourth respectively. A similar trend can be observed for the musical icons, with a 100% recognition rate in the first repetition, followed by 92%, 82% and 88% in the last three trials. The second musician performed less well in this task, reaching a 78% recognition rate for symbolic icons in trial one, 71% for trial two, 76% and 77% for trials three and four. For the musical icons, only 25% of the icons were correctly recognized in trial one, 66% in trial two, 77% and 57% in trials three and four.

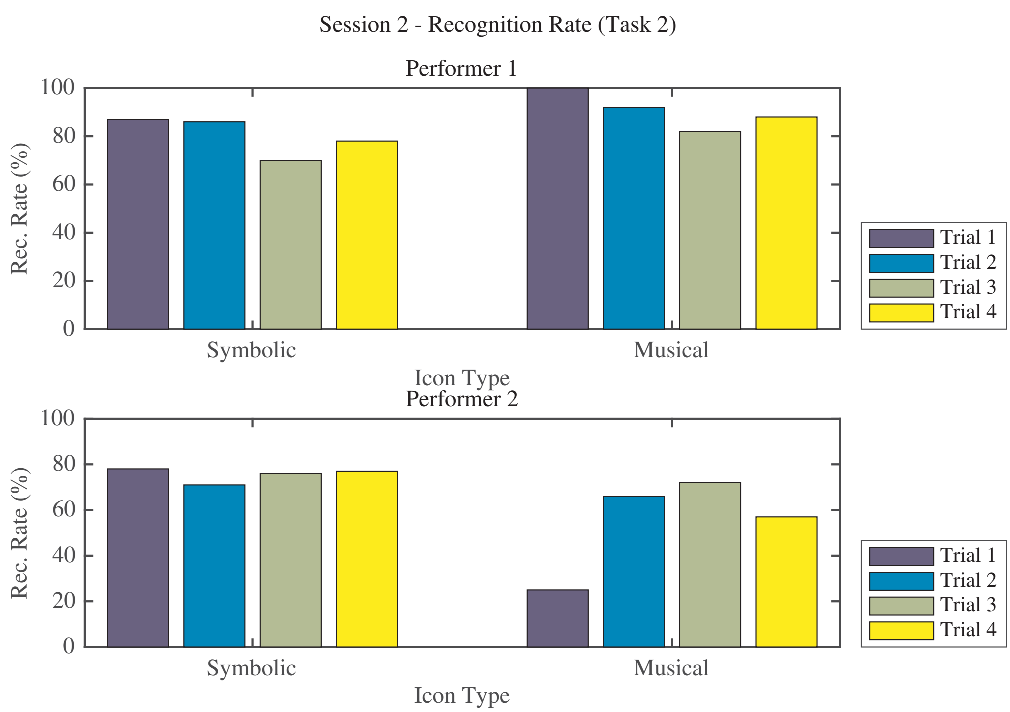
5.2.3 Musician's Feedback and Discussion

The two testing session with the undergraduate musicians show several patterns: performers' recognition rate in both sessions were consistently over 80% for task 1, even after only 20 minutes of practice with the belt. This suggests that, for both the musical and the symbolic icons, we were able to design learnable and distinguishable icons.

When looking at the data for the task 2, in both sessions, we can observe important differences between the two performers. Performer one consistently achieving better results than performer two: the latter stated that, especially in the second session, the



(a) Task 1 - Verbally report perceived icon.



(b) Task 2 - Play melody corresponding to the perceived icon as indicated on the score in Fig. 5.17.

Figure 5.19: Recognition rates for Session 2 for both Task 1 and Task 2. Both Symbolic and Musical icons were tested in this session. Results show recognition rates consistently around 80% for Participant 1, while Participant 2 performed less well in Task 2.

task could become quickly overwhelming. This suggests that the complexity of the task prevented him from simultaneously pay attention to both types of tactile icons and reading and playing the melodies on his instrument. He nonetheless improved his performance over time, as visible in Fig. 5.19b, by going from a 25% recognition rate for the musical icons in trial one to almost 80% in trial three.

Participant one scored above 80% in most of the tasks across the two sessions, and two trends can be identified: for both sessions, his performance in the musical task would decrease in trial three, compared to the first two trials. This might be due to the presence of adaptation effects which would decrease the sensitivity to the tactile icons. The musician stated that he did not find the tasks too demanding, and that the icon design would allow him to easily differentiate the tactile effects.

Overall, the variation between the two participants could be caused by their different proficiency on the instrument and habit to sight-read, notwithstanding their similar self-assessed musical expertise: participant one was very confident in the sight-reading and performance of the melodies we proposed, while for participant two this task proved to be quite demanding, as demonstrated by the frequent hesitation in performing the given melodies which can be heard in the audio recording of the testing sessions. The different posture adopted by the two musicians when playing the saxophone and the guitar respectively, could also be partly responsible for the variation between the two participants, but this aspect would require an investigation conducted on a larger group of musicians.

The observations reported above indicate that a satisfying degree of icon recognition can be reached for both musical and symbolic icons during the performance of a musical task, provided a high degree of confidence and expertise on the performer's side. While all the musical icons were equally well recognized during the two testing session, symbolic icons 5 and 6 were the most problematic ones in terms of recognition rates. Icon 5 would often be confused with icon 9 since, as reported by performer one, the vibration coming from the two actuators on the sides would sometimes go unnoticed. The peculiar geometrical pattern of icon 6 would instead make it difficult to recognized at times.

Ultimately, our result confirm that icons' transparency [MacLean, 2008] is not an absolute property of the icon itself, but is very much influenced by the global context in which tactile information is being transmitted to a user, and to his/her available cognitive resources [Qian et al., 2013].

5.2.4 Performance of Bhagwati's "*40 Icons about Art/Music*"

Sandeep Bhagwati composed "*40 Icons about Art/Music*", a first etude to be performed by trombone player Felix del Tredici wearing the augmented belt. The score, shown in Fig. 5.20, illustrates the architecture of the piece: the musician is instructed to recite, in sequence, the words contained in a 4 by 10 matrix; each word is then followed by the performance of a musical task, associated with a symbolic icon delivered by the belt. The four icons, marked with the capital letters A, B, C, D corresponded to icons 2, 3, 4 and 6 in Fig. 5.15, as selected by the musician during the first of the three rehearsals of the piece. The piece was performed on May 5th 2015 during the *EFFICACe Workshop* at CIRMMT[9].

We conducted three rehearsals prior to the performance of the piece. In the rehearsals the musician familiarized himself with the belt and the tactile icons by preforming a series of tasks similar to those described in the previous Section. At the end of the first rehearsal we finalized the set of four icons to be used in the piece by selecting those that the performer found more easily distinguishable (i.e. icons 2, 3, 4 and 6 in 5.15).

To meet the composer's needs we changed the symbolic icon sequencer by introducing two control parameters modifying the speed and intensity of the icons. These parameters, as explained in the score, influenced the performer's playing in each musical task.

5.2.4.1 Performer's Feedback

We submitted a questionnaire to the performer[10] to receive his feedback about his interaction with the belt. The questions concerned obtrusiveness of the garment, perception of motor vibration, icon design and overall system transparency.

The performer found the belt not to be obtrusive or hinder his movements. The skin-motor contact was judged to be satisfying, but he reported motor vibrations of the two actuators on his lower back to be "*quite difficult to perceive*". When asked about general

[9] `http://www.cirmmt.org/activities/workshops/research/efficace_workshop_2015/`

[10] The full questionnaire and performer's answers are reported in Appendix A

SANDEEP BHAGWATI

SKETCH PIECE #1 FOR BODYBELTSCORE

"40 ICONS ABOUT ART/MUSIC"

TEXT:

1	THIS	IS	REALLY	MUSIC
2	IS	IT	REALLY	ART ?
3	REALLY -	IS	THIS	MUSIC ?
4	IT	REALLY	IS	ART !
5	MUSIC	REALLY	IS	ART !
6	ART -	IS IT	REALLY	THIS ?
7	REALLY…	IS THIS	ART	MUSIC ?
8	ART	THIS IS	ART !	REALLY ?
9	IT	IS	THIS,	IS IT ?
10	IT IS !	IT IS THIS !	IT IS MUSIC !	IT IS ART !

INSTRUCTIONS FOR MUSICIAN:

At each icon, first recite the next word, then play the appropriate icon.

ICON A: PLAY A RUN OR ARPEGGIO UP OR DOWN (MIN 5 PITCHES)
ICON B: PLAY A MULTIPHONIC (SAME EACH TIME)
ICON C: PLAY ONE SINGLE OR A CLOUD OF SLAPS (VARIYING PITCHES)
ICON D: PLAY AND HOLD AN EXTREME PITCH (HI OR LO) – MODIFY ITS SOUND CONTINUOUSLY

In reciting and in playing the icon, take up the speed and movement of the icon.
The icons will come in random order, at random speeds and intensities.
Make Music from this - or Art.

Figure 5.20: Sandeep Bhagwati's *"40 Icons about Art/Music"*, the first sketch piece to be performed by trombone player Felix del Tredici wearing the augmented tactile belt.

thoughts about icons' design and learnability/distinguishability he commented that the icons' design allowed him to easily learn to recognize them, and that for a device like the belt he "*[c]ould not think of a better [communication] system*".

When asked about the impact of the belt on his attention and cognitive load during the rehearsal and performance of the piece, he commented:

"*I am wearing something, and I know that its actions will dictate what I do next, then it will take up a huge part of my brain. Fortunately, the piece was simple on paper, and I already knew what was coming next in some respects. So, that took the load off.*"

Commenting on the overall transparency of the system he explained:

"*I think the nature of wearing something that tells you what to do is already non transparent. [...] I would argue that if you wanted to make something that was transparent then the belt is not the way to go. It's not a bad thing, by the way. I'm just saying that the belt is there to be paid attention to.*"

5.3 General Discussion

Our work for the "Ilinx" garment resulted in the development of a robust, distributed system to control large arrays of ERM motors. While this approach is already found in other projects in the field of wearable haptics [Lemmens et al., 2009; van der Linden et al., 2011], our system features several advantages: it is based on off-the-shelf hardware and open-source software components; it features a modular design, which allowed us to take advantage of the technology we developed in several other related projects presented in the following Sections and Chapter; the control namespace we implemented can be easily addressed, by means of OSC messages, by many commercial or custom software environments. Moreover, we proposed the use of haptic envelopes as unit blocks to construct more complex effects, based on both temporal and spatial properties.

In the second project presented in this Chapter, we brought the technology developed for the Ilinx installation into the musical performance domain, by designing and evaluating the use of tactile icons to convey score information to expert musicians. As mentioned in Chapter 2, several researchers have evaluated the use of such icons [Brown, Brewster, et al., 2005], both in the context of localized, single-site solutions

[MacLean and Enriquez, 2003; Enriquez and MacLean, 2008], which are often delivered via actuators embedded in mobile phones [Maria Galdon et al., 2013; Kim, 2013], or multiple-site solutions using devices such as belts [Tsukada and Yasumura, 2004] or arm and back modules [L. A. Jones et al., 2009]. Researchers have also investigated the feasibility of using such icons in conditions in which users' attentional resources are limited [Chan et al., 2005; Qian et al., 2013], but results in this field are still not conclusive.

To our knowledge, no previous evaluation of the use of this type of tactile communications had been performed in the context of musical interaction. For our purposes, it was important to evaluate our tactile synthesis approach in the performance of real musical tasks. The evaluation we presented shows that our design paradigms for the tactile icons allows for recognition rate consistently around 80% after 20 minutes of familiarization with the system. The musical tasks we proposed, on the other hand, seem to impact these recognition rates in a way that is dependent on the users' musical expertise, and the effect of learning is visible already during a single session. Ultimately, the effectiveness of conveying score information via an abstract language of tactile icons would require extensive long-term studies, involving musicians using the same vocabulary of icons over several weeks or months.

These studies will be conducted in the continuation of the project, which will also feature the development of new garments and corresponding symbolic and musical icons. At the time of writing, a new belt, a jacket, and a leg module have been manufactured by the researchers at XS Lab, Concordia University, and are visible in Fig 5.21. These garments will allow, for instance, the systematic testing of the icons we proposed in Section 5.2.1, and the development of new icons, which will be integrated to the available set of icons for the belt.

5.4 Conclusions

In this Chapter we presented results in the context of the development of hardware and software solutions for tactile synthesis applications.

Firstly, we described the design of the tactile-augmented suits for *Ilinx*, a multisensory art installation, as well as the development of a small vocabulary of haptic effects.

(a) Leg module.

(b) Vest module and belt.

Figure 5.21: The new garments developed for the project. Design and manufacturing by J. Berzowska and A. Bachmayer — XS Labs, Concordia University.

The creation of these garments was driven by a perceptually-based methodology as well as by artistic and functional considerations. We focused on the haptic research that motivated the choice of actuator placement and effect design, and on development of custom hardware and software solution that were embedded in the tactile-augmented suits.

Secondly, we proposed a more systematical approach to the evaluation of the tactile icons designed for augmented wearables in the context of music performance. Our work was conducted in the context of *Musicking the body electric*, a four-year, multidisciplinary project aimed at developing specialized tactile augmented garments, as well as a language of tactile icons to be used in the creation of a wearable score system. Using the hardware and software platform developed for Ilinx, a set of specialized tactile augmented garment was produced and tested on musicians to deliver score information.The icons were delivered for the first garment produced, a six-actuator belt featuring ERM motors. A second actuator, attached on an elastic band, was also used to simultaneously deliver complementary information to the musicians.

Two types of tactile icons were designed and tested: symbolic and musical. The former consists of the icons delivered by the belt, which feature a combination of spatial and temporal patterns and an arbitrary mapping to a given musical task — hence requiring musicians to learn the icons and their corresponding mappings. The latter, corresponds to icons delivered by the single actuator, designed to elicit a natural correspondence between the icon's temporal envelope and the musical task it corresponds to — dynamic and articulation cues. A preliminary evaluation of the icons on two undergraduate musicians showed that both types of icons can be reliably identified in a verbal recognition task. When asked to perform a musical task, musicians can also reliably recognize the icons and perform the corresponding melody, provided that the musical tasks itself is not already too demanding given the musician's ability and experience.

The device was used for the performance of a first etude by composer S. Bhagwati, in which four of the ten icons were selected by the musicians performing the piece to represent four musical tasks. We reported the performer's feedback after the performance, who praised the icon design while at the same time stressing the intrinsically demanding nature of the task proposed by the composer.

Chapter 6

Designing Tactile Notifications: A Tactile Metronome System for Music Performance

In this Chapter we present the development of two tactile notifications systems for musical interaction, in the context of delivering notifications about the state of a live-electronics environment for music performance, and conveying tempo information to an ensemble by means of a tactile metronome system. For both systems we describe their hardware and software implementations as well as the choices behind the design of the tactile effects delivered to musicians. For the tactile metronome, we also provide a perceptual evaluation of the effectiveness of such a device.

6.1 Development and Evaluation of a Tactile Notification System for Live-Electronics Performance[1]

The term live-electronics refers to the practice of live processing of acoustic sound produced during a performance by means of dedicated machines and sound processing environments. Performers on stage are often required to interact with such systems, and the type of interaction and its repercussions on the musical act as a whole can be challenging aspects in contemporary performances [McNutt, 2004]. Musicians, for instance, are required to use on-stage controllers such as foot switches or pedals, which are used to control effects or cue the beginning of movements or Sections in the live-

[1]This Section is based on *"Vibrotactile Notification in Music Performance: A Prototype System"* - M. Schumacher, M. Giordano, M. M. Wanderley, and S. Ferguson - Proceedings of CMMR, 2013.

electronics piece. The response of the system to these commands is not necessarily available to the performer, who is often left in a sort of temporary "limbo" in which he/she does not have any direct feedback about his/her interaction with the system.

A common approach to overcome these issues is to provide performers with visual or auditory displays, such as on-stage screens showing in real time the state of the live-electronics system. An external assistant can otherwise be assigned with the direct control of the live-electronics system. Both these approaches present some evident drawbacks: the former can burden significantly the musician's cognitive load, and limit his/her attention to other crucial tasks — such as following a score, listening to system-produced sounds, cue or respond to other musicians' cues; the latter, by removing the need of a direct performer-system communication, radically contradicts the idea of a truly interactive performance.

The aforementioned limitations require a new approach to be undertaken in order to conceive a system capable of taking the performer out of this temporary limbo, while guaranteeing true interactivity and interface transparency [MacLean, 2008].

The literature presented in Chapter 2 indicates that the sense of touch can be an ideal candidate as target sensory channel to convey musically relevant cues, especially in the context of live-electronics interaction. As already mentioned, Michailidis et al. [Michailidis and Berweck, 2011] for instance, developed a tactile notification tool for delivering feedback about the successful activation of an effect via a foot pedal.

For these reasons, we decided to developed a tactile notification system for CLEF, the CIRMMT Live-Electronics Framework[2] by Marlon Schumacher and Sean Ferguson, currently maintained by M. Schumacher. The system features a hardware display composed of two ERM actuators, and a software module embedded in the composition environment.

CLEF is a modular environment for composition and performance, developed in Max, which has been used extensively for both composition and teaching purposes. CLEF features a score system and modules implementing functionalities such as real-time signal processing, spatialization, looping and other techniques typically associated with live-electronics contemporary music. Control parameters and internal communication rely on Open Sound Control (OSC) messages transmitted via a shared bus. CLEF's architecture enabled us to develop a tactile notification system seamlessly in-

[2] http://clef.sf.net

tegrated into the composition environment, making mapping of effect parameters, or system state to tactile cues extremely easy.

The development of the tactile notification system was done in collaboration with a performer, percussionist Preston Beebe, whose feedback determined many of the design choices presented in this Section.

6.1.1 Hardware Prototype

The hardware prototype is composed of two ERM motors, of the type characterized in Chapter 3. The prototype is composed of a Velcro band to which the two motors have been attached. The band can be securely worn around the upper chest, so that the motors are in firm and direct contact with the performer's back at all times. The motor's position, symmetrical around the spine, was determined after several testing session with the performer involved in the project. The position was judged unobtrusive and would not hinder his movements and respiration. Moreover, this configuration allowed, as we will see, the development of two types of tactile effects: localized actuation using one or both actuators and a continuous motion from one side to the other side of the performer's back.

To control the motors, an Arduino board was used to transmit PWM signals. The Firmata protocol[3] was used to interface the microcontroller connected via USB to the computer running CLEF.

6.1.2 Tactile Effects and Mapping

A tactile notification engine and user interface were implemented in CLEF to function as a bridge between the software and the hardware prototype. We designed several tactile effects and a OSC namespace to access them; thanks to the shared message bus available in CLEF these effects could readily be mapped to events or parameters in the composition environment.

Figure 6.1 shows the user interface built on top of the tactile notification engine. The interface allows a direct control over the tactile display using the available knobs and triggers. On the right side of Fig. 6.1 the notification engine namespace is visible with

[3] `https://github.com/firmata/protocol`

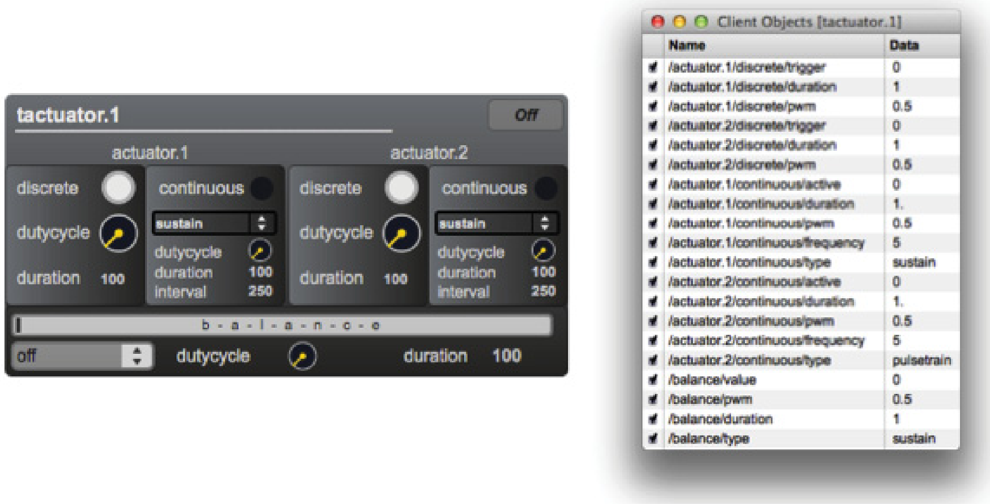


Figure 6.1: The user interface associated with the tactile notification engine as implemented by M. Schumacher. The namespace and default values for the module control parameters can be seen on the right.

its default values. Each effect can be triggered by sending the corresponding message using the environment's message bus.

The tactile notifications available in the module can be divided into three categories: *discrete*, *continuous* and *balance*. The first two are available for each actuator separately (*actuator.1* and *actuator.2*), while the last effect is achieved by a simultaneous activation of the two motors. The *discrete* effect provides a single, *buzz*-like activation whose duration and intensity (via the *dutycycle* parameter) can be chosen arbitrarily. These effect can be mapped to single events taking place in the composition environment, such as the beginning or ending of a Section, or as a response to a user's interaction with an on-stage controller. The *continuous* effect features two modes of operation, *sustain* and *pulsetrain*. In sustain mode, the actuator keeps vibrating at the intensity set by the dutycycle variable, until a switch-off signal is sent to the tactile engine. This mode can be used to represent the state of time-varying variables in one of the system's modules. The pulsetrain mode features two extra control parameters: duration of each of the pulses and interval between each subsequent pulse. This type of effect can be used, for instance, concurrently with the continuous mode and represent the state of a second module's internal state. The *balance* effect features the simultaneous vibration of both actuators, whose intensities are relatively adjusted using a cosine panning law: by selecting a value in the -1 to $+1$ range, the relative intensity of the motors can be adjusted and used to represent, for instance, horizontal position of a sound or, more generally, position of a point on a straight line.

6.1.3 System Evaluation

The tactile effects we described were used in a performer-based evaluation, for which we designed two distinct musical tasks to be performed on a drum kit. The performer participating to our evaluation was already familiar with the CLEF environment but had no previous experience with vibrotactile-augmented displays of any sort. After the performance, which took place during the CIRMMT Student Symposium in 2013, the performer completed a short questionnaire evaluating his experience with the system.

The first task consisted in a short improvisation performed using a technique known as "overdubbing": a performer records a musical phrase in a buffer and subsequently plays a new sequence along with the previous recording. This new sequence is then also recorded, and by repeating this process several times new, more complex structures are created. In our task, the overdubbing parameters had been already scripted in CLEF and the performer would only need to launch the sequence by means of a foot switch. After activating the controller, the performer received two bars of pre-count (at 120 BPM tempo) before the start of the recording of the first musical phrase. These two bars were delivered as a sequence of strong *discrete* vibrations to one of the actuators, and continued throughout the performance, acting as a tactile metronome which would cue the musician to follow the target tempo for each of the recorded loops.

In the second task, we used the *balance* effect to represent the position of a sound source moving on a horizontal line. CLEF was programmed to receive the live input from the performance and process it through its spatialization module. The output was then fed to two speakers standing beside the performer, producing the effect of a sound moving from the left to the right speaker, in a time varying between 3 and 5.5 seconds. The position of the sound was mapped to the tactile module, and the performer could feel the vibration shifting in intensity from it left to right side and vice versa. Given the position of the speakers, the performer had to rely entirely on the vibrations to determine the position of the sound as perceived by the audience. Using this setup, he was asked to improvise short musical phrases at different tempi and on different elements of the drum kit, according to the position of the sound on the horizontal line.

These two simple tasks show that tactile effects can convey information on several levels. In task one, the two bars of pre-count act firstly as direct feedback on the successful activation of the recording process, and secondly as a way to convey musical information at the score level (i.e. the tempo of the performance decided by the composer). In task two, the continuous vibration is a direct notification to the performer of the internal state of a variable in one of the system's modules (i.e. the horizontal position of the output sound on as perceived by the audience).

6.1.4 Performer's Feedback

After the performance, a questionnaire was submitted to the musician to assess the quality of his experience with the system.

When asked about the effectiveness and obtrusiveness of the hardware prototype he remarked that:

- The system was very effective at displaying temporal information (task one);
- The spatial information was also transmitted clearly it was easy to distinguish the position of the sound (task two);
- The musician found the display comfortable to wear, and he judged it to be unobtrusive and not hindering his natural movements.

When asked about the effectiveness of the tactile effects compared to other sensory modalities, he responded that:

- In terms of obtrusiveness, tactile feedback rated second best after visual feedback and before auditory feedback. He judged auditory feedback to be extremely interfering, while he considered that visual feedback would not interfere at all with his musical practice;
- The musicians remarked that a combination of tactile and visual feedback could be used to display the state of multiple variables in the system at the same time;

- Tactile feedback was judged to be an essential feedback modality in the case of a performance in which the musician needs to focus his attention on the score, or for a piece in which direct visual contact is needed between several performers. The performer remarked that, for instance, tactile feedback would be the ideal solution to convey individual tempo cues to members of an ensemble.

Overall, the performer stated that the proposed tool could be integrated in his future rehearsals and performances. In terms of possible improvements, he remarked that elastic Velcro bands could improve the system's comfort and that multiple actuators could allow for a wider range of tactile effects.

6.2 Evaluation of the Effectiveness of a Tactile Metronome in Music Performance[4]

Given the positive feedback expressed by the performer participating in the project we described in the previous Section, we decided to conduct a more systematic evaluation of the effectiveness of a tactile metronome system.

The concept of a tactile metronome has already been proposed in the past and several patents for tactile metronome devices have been filed in the last decade [Parsons, 2004; Fulford, 1999]. Moreover, commercial tactile-augmented products have started to appear on the market [Peterson Tuners, n.d.; Soundbrenner, n.d.], claiming to be able to provide musicians with reliable tempo cues. No quantitative evaluation of the capability of the sense of touch to process such information, in the context of music performance, has nonetheless been conducted so far [Repp, 2005]. Most of the literature in the field of synchronization studies to a tactile beat is limited to tapping experiments [Brochard et al., 2008], in which participants are not actively engaged in any activity. The results from these experiments, while still valuable to evaluate the performance of tactile perception in synchronization tasks, cannot be directly applied to the context of music performance.

The development of the aforementioned commercial products, although not supported by perceptual evidence, testifies nonetheless the interest of researchers, industry

[4]This Section is based on *"Follow the Tactile Metronome: Vibrotactile Stimulation for Tempo Synchronization in Music Performance"* - M. Giordano and M. M. Wandeley - Proceedings of SMC, 2015.

and general public for haptic-enabled interfaces targeted to musicians.

With this study, we aimed at performing a quantitative evaluation, by providing evidence that vibrotactile stimulation can proficiently be used to convey tempo information in music performance. We designed a synchronization tasks in which participants are actively engaged in musical task: performing an ascending and descending scale on a classical guitar.

6.2.1 Experiment

Four guitar players[5] were asked to play the first seven notes (ascending and descending) of a G major scale while synchronizing to either a tactile or an auditory metronome. The G major scale is generally recognized as an easy exercise for experienced players and was hence chosen so not to present participants with a too demanding task [Wright et al., 2012], while at the same time, engaging them in an ecologically valid musical task. The tactile stimuli were delivered through a display attached to their left upper arm, while the auditory stimuli were delivered via headphones.

6.2.2 Tactile Display and Metronome Signal

One of the EMR actuators described in Chapter 3, driven by an Arduino board and a ULN2803A motor driver was used to deliver the metronome signal.

The intensity was set to a 0.8 value for the duty-cycle of the PWM wave; this value is well above the perceptual threshold, as remarked in Chapter 3. The intensity value remained constant throughout the tests and across participants.

The actuator location on the left upper arm (see Fig. 6.2) was chosen mainly because it did not hinder participants movements, and because sensitivity in this area is reported to be high enough to allow reliable perception of the tactile metronome signal [Bikah et al., 2008]. Other locations were tested: the left wrist was judged by the performers as obtrusive and disturbing; the left ankle caused some stimuli to go undetected since some of the non classically trained participants tended to tap along the tempo with their left foot.

[5] Participants reported having at least 3 years of practice on the instrument

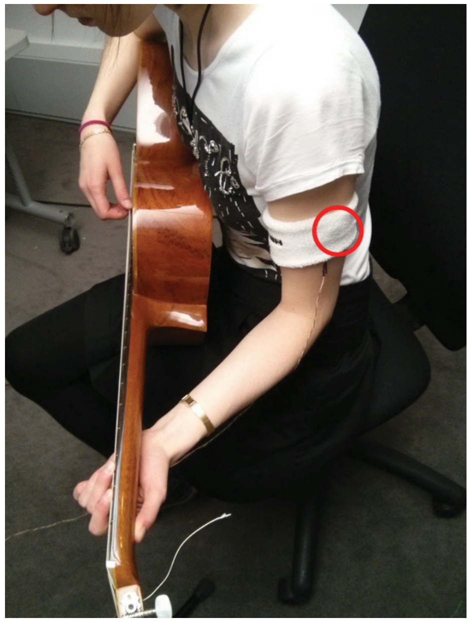


Figure 6.2: One participant wearing the tactile display on her left arm (circled in red).

A software control environment written in Max was designed to generate synchronized tactile and auditory metronome tracks, and to record musicians' performance. The auditory metronome was delivered through headphones connected to an external RME Fireface 400[6] audio interface. Only the left channel was used to match the lateralization of the tactile stimulus. Headphones were also used to deliver quiet white noise to mask actuator noise during the tactile metronome trials.

The overall latency of the system was also evaluated: a PCB Piezotronics 35C23 one-axis accelerometer was attached to the actuator. The output from the sensor was connected to the external audio interface input. We estimated the delay of the interface to be to the order of 2.5 ms: this was done by looping the output back into the input, and using a Max input-output buffer. Using this setup, the delay between the serial commands sent to the Arduino board and the activation of the motor was evaluated to be in the order of 3 ms. Frid et al., [2014] evaluated to 15 ms the time needed for the actuator to reach its supra-threshold amplitude vibration from a steady state. Hence, the system combined (i.e. mechanical and perceptual) total delay was estimated to be around 18 ms. For the auditory metronome and recording system, the aforementioned

[6] `https://booking.cirmmt.org/media/model/71/fface400_e.pdf`

audio interface was used. We assumed the delay added by transmission through the headphones and microphone wires to be negligible, thus obtaining an overall delay for the recording apparatus and auditory metronome to be in the order of 2.5ms. These delays have been taken into account in the analysis of the data.

6.2.3 Procedure

To ensure that neither the auditory nor the tactile metronome stimuli would be perceived as stronger, an equalization phase was performed for each participant prior to the beginning of the experiment. Each was presented with both the tactile and the auditory click-tracks and asked to evaluate the *perceived intensity* of the auditory track relatively to the tactile one, which was fixed as reference. Participants instructed the experimenter to increase or decrease the volume of the auditory click-track in order to match the perceived intensity of the two stimuli. Subsequently, participants were exposed to four metronome conditions, varying sensory modality and metronome speed (expressed in Beats Per Minute, or BPM) in random order:

- Tactile Metronome at 120 BPM,
- Tactile Metronome at 60 BPM,
- Auditory Metronome at 120 BPM,
- Auditory Metronome at 60 BPM

Participants were asked to play synchronously with the metronome track while being recorded through a microphone. They could start their performance at any time after the metronome signal had started, and each recording session lasted 60 seconds (i.e. after they played 120 notes at 120 BPM or 60 notes at 60 BPM). Participants performed each condition only once.

We decided to test only two tempi. The 60 and 120 BPM values were chosen since they are generally associated by musicians to, respectively, a slow and a fast tempo [Duke, 1989].

6.2.4 Results

The audio files were analyzed to extract onset information from participants' performances. We manually annotated the onset on the audio files to match the attack of each guitar pluck (see Fig. 6.3). Interpolation was used to compensate for missing plucks.

These onsets were compared to the metronome signal in order to evaluate participants' asynchrony in each modality, moreover participants' deviation from the target tempo was also evaluated.

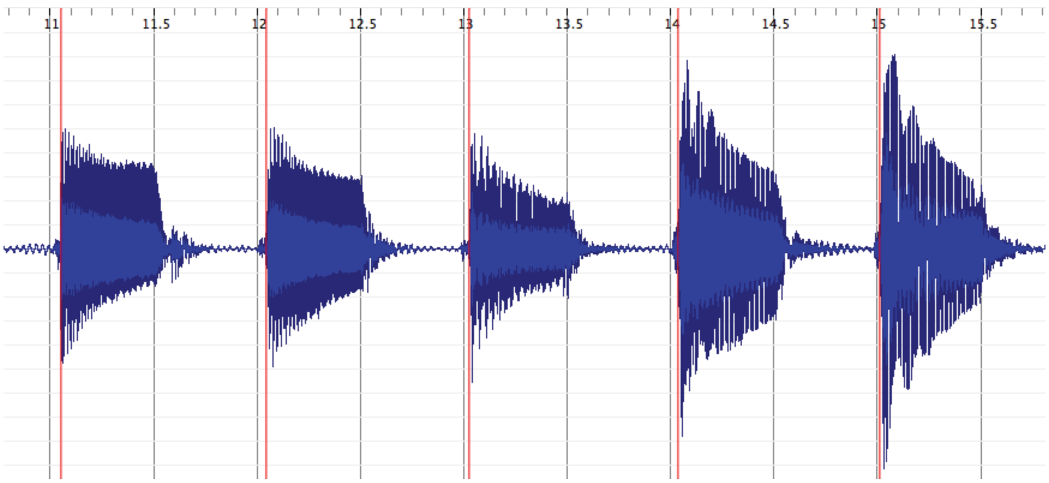


Figure 6.3: An excerpt of one performance (60 BPM Tactile). Recorded guitar plucks are shown in blue. The red lines indicate the manually annotated onsets. Time scale is visible on the top (time in seconds).

An asynchrony vector (representing participants' *lag* or *delay* with respect to the metronome signal) was computed for each participant by subtracting plucking-time vectors to metronome-time vectors. This is shown in Fig. 6.4, which depicts the asynchrony data for the entire data set of plucking times (240 data points at 60 BPM, 480 at 120 BPM) plotted per participant over time. The average results across participants are shown in Table 6.1 and Fig. 6.5. Participants' performance over time show a similar behavior between participants, especially at 60 BPM for both the tactile and auditory metronomes. At 120 BPM, much more variation is present in the tactile modality, and the between-subject differences are much more pronounced. On average, plucks happen after the corresponding metronome signal and this delay is more important for the tactile modality. Overall, this suggests, in accordance with findings reported in the psycho-physical literature [Lederman and Klatzky, 2009], that the processing time for the tactile metronome signal is higher than for the auditory one.

Figure 6.6 shows deviation time from the target tempo participants were supposed to follow plotted over performance time. This is expressed as a deviation from target

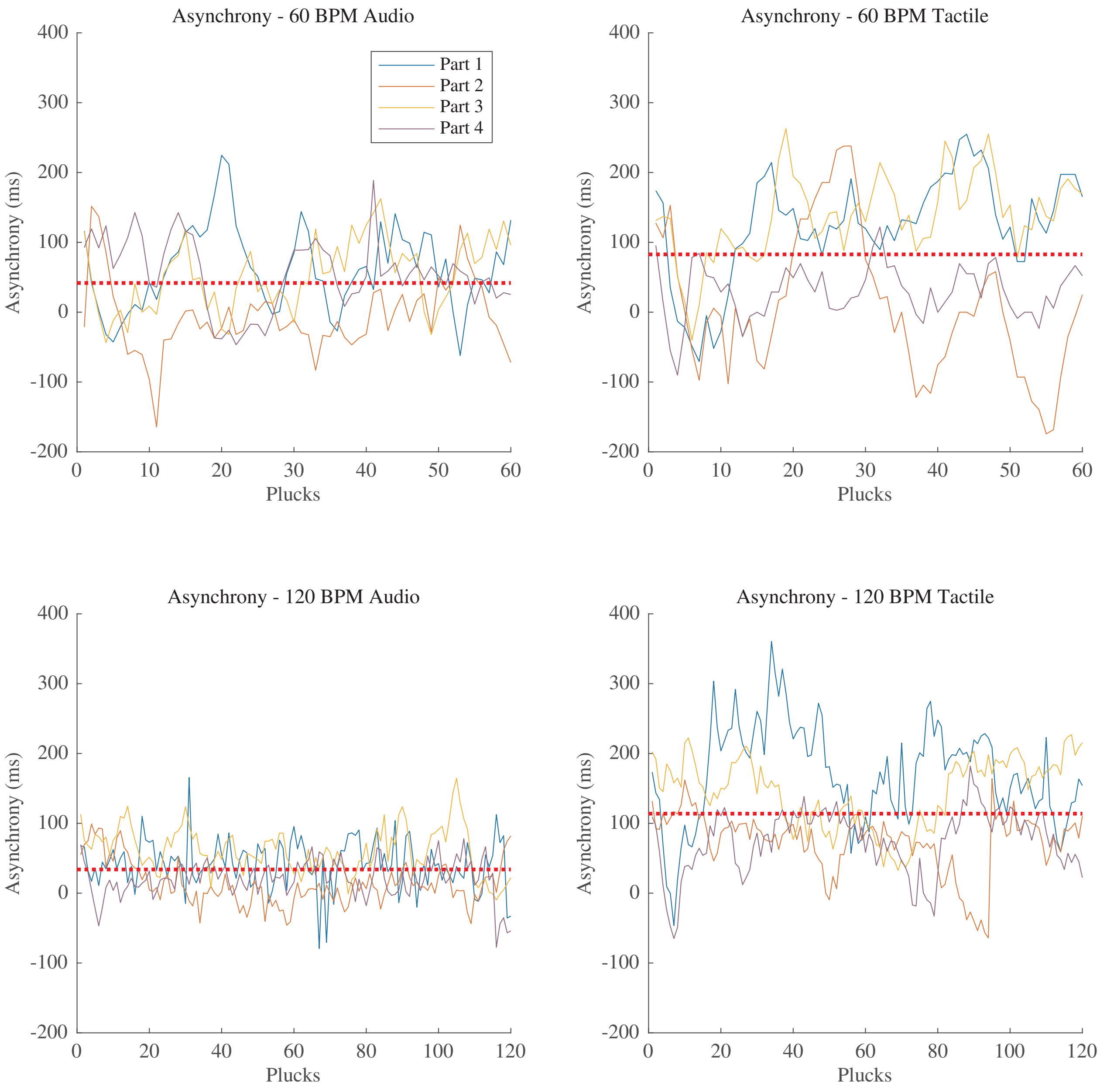


Figure 6.4: Asynchrony from the metronome signal for each recorded guitar pluck, plotter per participant over the performance time. The top row shows asynchrony for the 60 BPM tempo, the bottom row corresponds to 120 BPM. Audio modality is on the left column, tactile on the right. The red dotted lines indicate the mean value across participants.

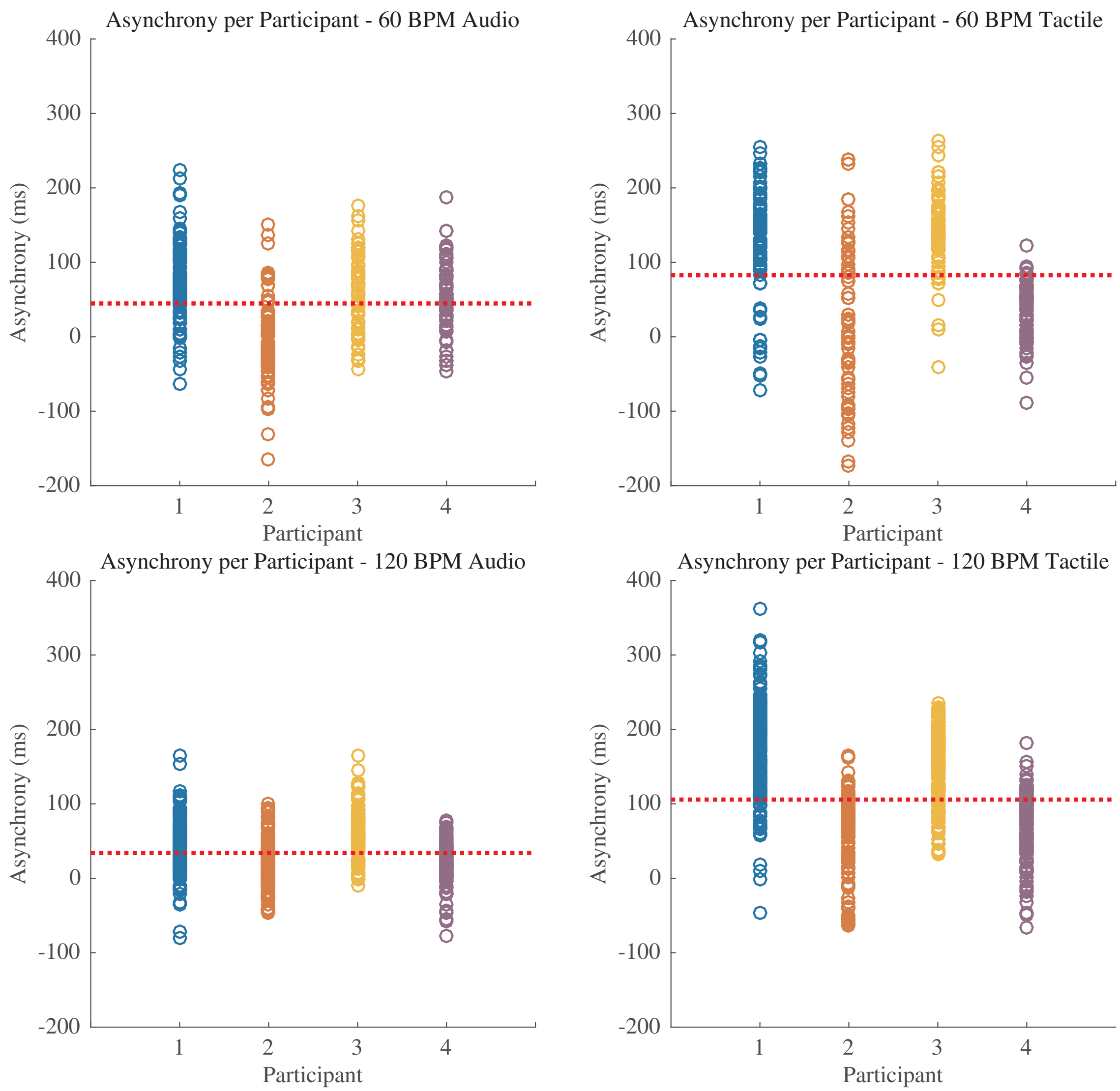


Figure 6.5: Asynchrony from the metronome signal for each recorded guitar pluck, plotter per participant. The top row shows asynchrony for the 60 BPM tempo, the bottom row corresponds to 120 BPM. Audio modality is on the left column, tactile on the right. The red dotted lines indicate the mean value across participants, as indicated in Table 6.1

Modality	60 A	60 T	120 A	120 T
Asynchrony (ms)	41.77	82.73	33.93	113.85
S.D.	59.2	86.64	35.53	70.72

Table 6.1: Average asynchrony times across participants for each modality (A for auditory metronome, T for tactile metronome) with their Standard Deviation (S.D.) Positive values indicate that, on average, the plucking happened after the metronome tick. These asynchrony values were processed taking into account the system delay as reported in Section 6.2.2.

Modality	60 A	60 T	120 A	120 T
Deviation (ms)	-0.12	-0.67	-0.18	-0.47
S.D.	36.69	38.98	24.47	24.64

Table 6.2: Average deviation from target IOI across participants for each modality (A for auditory metronome, T for tactile metronome), with their Standard Deviation (S.D.)

IOI (Inter Onset Interval, expressed in milliseconds). Fig. 6.7 and Table 6.2 show the average data and standard deviation across participants. Participants' deviation from the target tempo is around zero for the four conditions, with oscillations expressed by the standard deviation (S.D.) value which are slightly more pronounced for the tactile modality. The temporal evaluation in Fig. 6.6 also shows more consistent behaviors between the two modalities.

We performed a Wilcoxon rank-sum test to assess if the data, taken as a whole after removing outliers, come from the same population. The rank-sum test rejected the null hypothesis that asynchrony for tactile and audio modality comes from the same population for both the 60 BPM ($p < 0.05$) and 120 BPM ($p < 0.05$). The same test failed to reject the null hypothesis for the deviation data, again for both 60 BPM ($p > 0.05$) and 120 BPM ($p > 0.05$).

6.2.5 Discussion

Results show that participants' reaction time to the metronome ticks delivered via the tactile display is significantly slower than for the auditory click-track. Also, the response time fluctuates considerably around the mean value for the tactile modality, suggesting that adaptation and masking effects might influence the perception of the

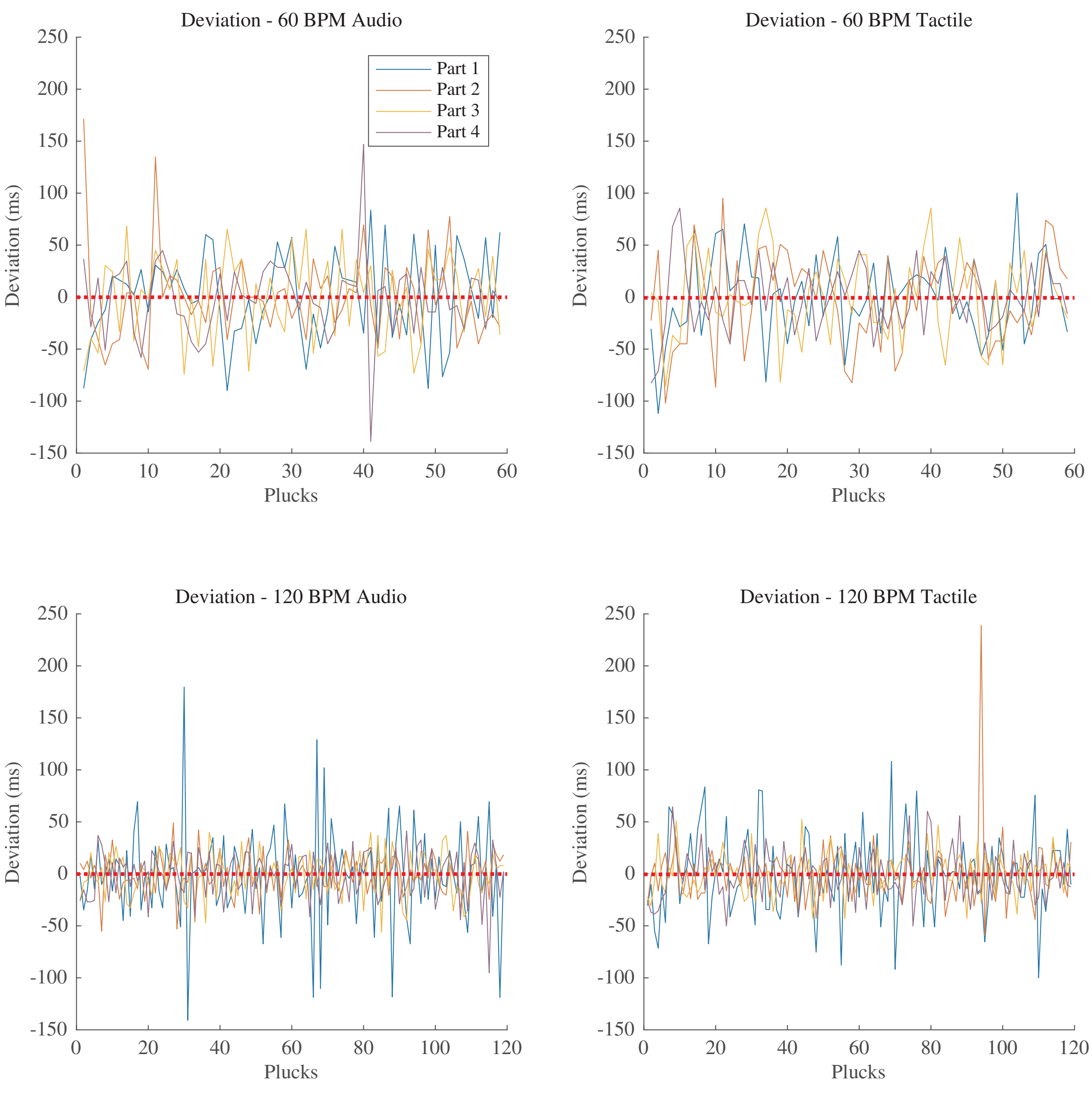


Figure 6.6: Deviation from target IOI for each recorded pluck, plotted per participant over performance time. The top row shows 60 BPM tempo, the bottom row corresponds to 120 BPM. Audio modality is on the left column, tactile on the right. The red dotted lines indicate the mean value across participants.

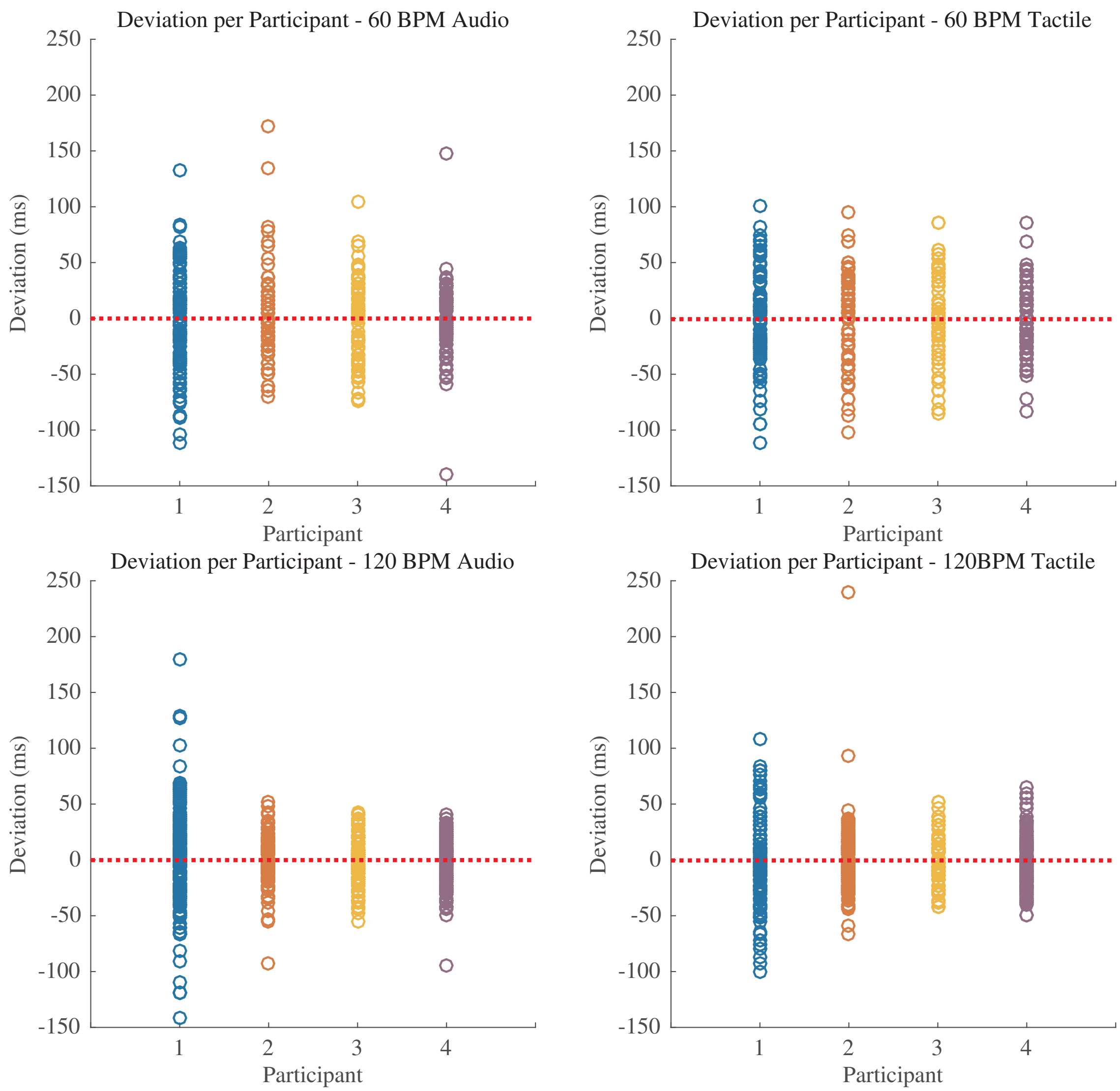


Figure 6.7: Deviation from target IOI for each recorded pluck, plotted per participant. The top row shows 60 BPM tempo, the bottom row corresponds to 120 BPM. Audio modality is on the left column, tactile on the right. The red dotted lines indicate the mean value across participants, reported in Table 6.2.

tactile stimuli during the performance of the task.

The deviation-from-target-IOI analysis shows instead no significant difference between modalities. This suggests that using a tactile click-track, participants are capable of following the target tempo as accurately as with the auditory metronome. For the 1000 ms target (60 BPM), the mean deviation value is around 0 for both modalities, and the magnitude of fluctuation is comparable. For the 500 ms target (120 BPM), the median is also at 0 for both modalities with less fluctuation compared the 1000 ms (60 BPM) target.

Overall this analysis indicates that a tactile metronome can cue performers to follow a given target tempo with an accuracy comparable to that of an auditory click-track. On the other hand, participants seem to react to the tactile metronome ticks later than the auditory ticks. In the case in which absolute timing accuracy with respect to the metronome is necessary, this delayed reaction could be compensated for by anticipating the tactile-click track.

6.3 A Distributed Vibrotactile Metronome for Ensemble Performance

As we mentioned, the haptic metronome notification proposed in the Section 6.1 proved to be very effective and highly rated by the performer. Moreover, the results presented in Section 6.2 confirmed that a tactile metronome system can proficiently be used to cue musicians to follow a target tempo. Such a system could be particularly effective for ensemble performances, in a context in which auditory click tracks would otherwise be used (see performer's feedback in Section 6.1.4).

Given these results, we decided to continue the development of a tactile notification system, with the aim of delivering tempo information to ensembles. This motivated us to purse a collaboration with CLEF's developer M. Schumacher and composer Fredrik Gran[7], who composed *"Champs Magnétiques"*, a piece for saxophone quartet which features a complex polytemporal structure.

We developed a multi-user tactile notification system which we used to deliver in-

[7] `http://fredrikgran.com/`

dividual metronome signals to the performers of Gran's piece, the Quasar[8] saxophone quartet. Champs Magnétiques was performed in March 2015 at the Gesù - Centre de Créativité[9] in Montreal.

6.3.1 *"Champs Magnétiques"*

Since its early conception, Gran's piece was composed specifically with the aim of being performed by musicians wearing a hidden, tactile notification system.

Each of the eleven movements comprising Champs Magnétiques, features a complex, polytemporal structure, in which each of the four voices is at a different tempo. The piece explores the duality between performers' "inner time" and the piece's "global time": the tempi for each voice in a given movement ("inner time") are arranged so to produce coincidental rhythmic events throughout the piece (hence emphasizing the "global time" aspect), in which performers are synchronized (see Fig. 6.8). Exact timing is an essential requirement for a successful performance.

Moreover, the piece features a rich sonic texture, in which multiphonic sounds and other extended techniques play a major role. Performers' ability to listen to each other is crucial to maintain a balanced soundscape, but this task is made more difficult by the physical placement of the performers on stage, which is depicted in Fig. 6.9: the musicians are "isolated", disposed along a circle, facing outwards towards the audience, eliminating the possibility of coordination by means of visual cues.

Given the peculiarities of the piece, the performers' strongly opposed the use of auditory click tracks to deliver the metronome signals, since this would have hindered their ability to listen, in a context in which they have no direct line of sight with each other. The tactile metronome system represented a perfect solution to respond to the composer's and performers' needs, and the design of the tactile notifications was the direct result of Quasar's feedback during rehearsals.

[8] `http://www.quasar4.com/`
[9] `http://www.legesu.com/`

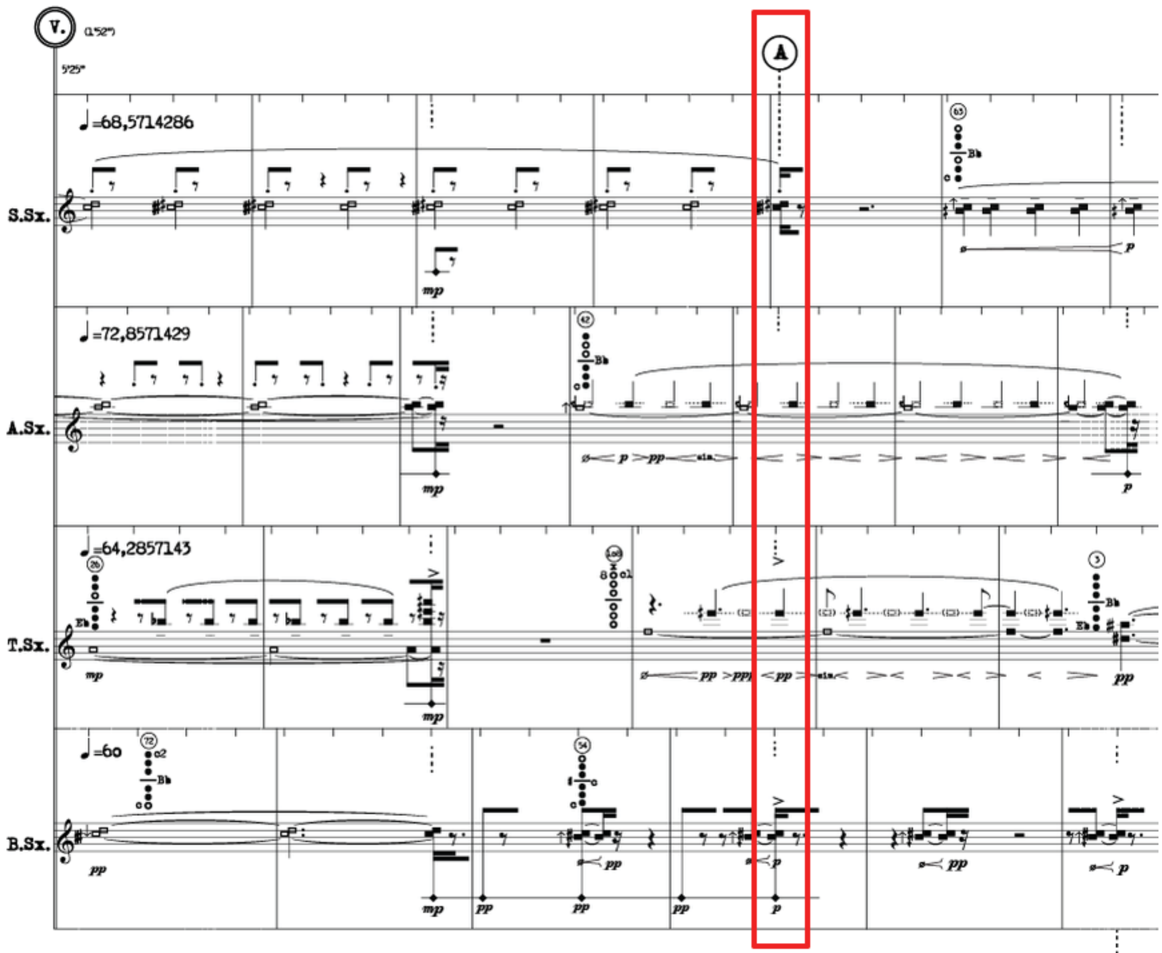
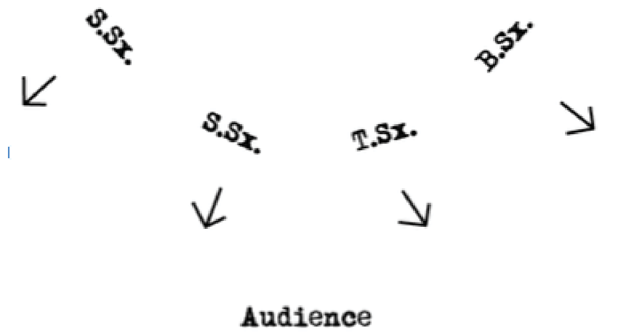


Figure 6.8: An excerpt from the score of the fifth movement of Champs Magnétiques with the tempi for each voice visible on the left side. The vertical red box marks a rhythmic event in which the four voices coincide for only one beat.



(a) Performers' placement as indicated by F. Gran on the score.

(b) Quasar performing Champs Magnétiques (photo courtesy of M. Schumacher).

Figure 6.9: The "isolated" performers, facing outwards while performing Gran's piece.

6.3.2 Tactile Metronome System and Notification Design

6.3.2.1 Hardware and Software

The tactile metronome system is composed of four control units, which encapsulate the electronics needed to drive up a VPM2 ERM motor. The IC contained in the control unit is the LB1837M3 driver, which we characterized in Chapter 3. Each unit presents a mini-jack connector on the front panel, which is used to connect a ERM actuator attached to the other hand of the cable, as visible in Fig. 6.10a. For this project, only one actuator was configured and used to deliver the tactile metronome signal. An Ethernet connector on the back of the unit is used to connect each of them to the central node (a BeagleBone Black[10] mini-computer) responsible of dispatching the OSC messages coming from a laptop running CLEF. For the development of the system hardware, we took advantage of the hardware we contributed to develop in a previous project, which we described in detail in Section 5.1.

The custom-built enclosures (3D modeled by Loïc Billoët) were 3D printed using the facilities available at CIRMMT. The enclosure's size permits an easy fit in a pocket, and each of them features a belt clip at the bottom (see Fig. 6.10b). The control units can also be used individually, for practicing or solo performances, without the need of being connected to the central node: a mini-usb port on the back panel can be used to connect it to a computer running CLEF, which will automatically deliver the required serial messages.

Leveraging our previous work, we updated the tactile notification engine available in CLEF with a new version of the module. Several instances of the module can be created, and each is capable of addressing one control unit separately. A "haptic envelope" message can be designed in the module by controlling the attack, sustain, release and amplitude sliders (see Fig. 6.11a). This system provides a higher degree of flexibly in designing haptic effects, by adding a temporal dimension to the tactile cues, which was not achievable in the previous version of the module. As we will see, different temporal envelopes can be mapped to distinct events taking place in the piece. Continuous effects can also be achieved by continuously modulating the amplitude parameter.

The signal-based timing system available in CLEF (see Fig 6.11b) was used to generate the metronome signals. These are generated in the DSP, hence allowing for sample-

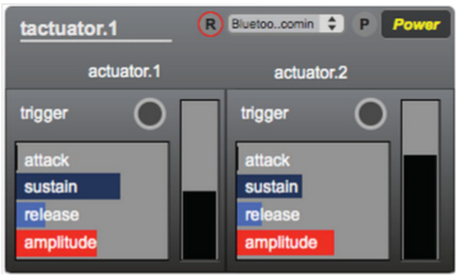
[10] `http://beagleboard.org/black`

(a) One of the control units, featuring a mini-jack connector, visible on the front panel, to easily connect an ERM motor (visible in the back). L. Billoët 3D modeled the unit's enclosure.

(b) Quasar baritone sax Jean-Marc Bouchard rehearsing F. Gran's piece. The control unit is clipped to his belt, and he is wearing the actuator on his left elbow.

Figure 6.10

accurate timing and phase locking between several instances of the metronome module. Using the system's message bus, timing information can be mapped to the tactile notification engine, triggering a pre-programmed haptic envelope.



(a) The new tactile notification engine (identified in the CLEF module catalog as "Tactuator"). Each module supports up to two actuators, for which individual haptic envelopes can be designed and triggered.

(b) The signal-based metronome system available in CLEF was used to generate the metronome messages. All the instances of the metronome modules use the same time generator, guaranteeing synchronization of each metronome track.

Figure 6.11: The tactile notification GUI and metronome module, implemented in CLEF by M. Schumacher.

6.3.2.2 Tactile Notifications Design

Throughout the rehearsal sessions with Quasar, we tested several notifications to deliver the metronome signal. One of the earliest requests was the differentiation between the downbeat and the subsequent upbeats in each measure. This was achieved by modulating the temporal envelope of the tactile click track, as depicted in Fig. 6.12. The downbeat vibration was designed to have a sharp attack (0 ms), 150 ms sustain and 100 ms release time; the upbeats also feature the same sharp attack but have shorter sustain (100 ms) and no release time.

Quasar members emphasized the need for a strong vibration signal, and reported a loss of sensitivity which would result in a less prominent haptic click track towards the end of the piece. This was likely the result of sensory adaptation [Orr et al., 2006]. To overcome this problem, we decided not to use vibration amplitude as a parameter to model different notifications. Instead, we implemented a linear increase of the overall intensity of the vibrations throughout the piece (from 60% to 100% dutycycle). This resulted in sufficient compensation for the adaption effect, and provided the musicians with a satisfactory intensity level from the start to the end of the performance.

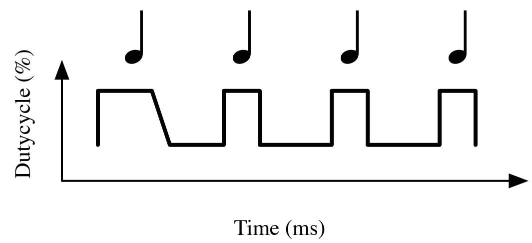


Figure 6.12: A representation of the haptic envelopes used to deliver the downbeats and upbeats in the metronome signal.

During the rehearsals, performers expressed concern due to their difficulty in finding points of reference in the piece. This was accentuated by the sparse sonic nature of the piece itself and by the lack of direct visual feedback with each other. Since a new movement would usually coincide with a change in tempo, they demanded a new type of notification, to mark the end of a movement and the beginning of a new one.

At this stage in the project, we had committed to the use of only one ERM motor, which was already occupied delivering a constant metronome beat. The only viable option to integrate the new notification was to deliver it via the metronome signal. This is depicted in Fig. 6.13: for the last bar of a movement, the metronome signal would count in eight-notes instead of quarter-notes. This design proved to be valid in terms of providing Quasar with the required information, without compromising the effectiveness of the metronome signal.

6.3.2.3 Actuator Placement and Performance Setup

Each member of Quasar freely chose where to place the ERM motor used to deliver the tactile metronome signal. The soprano opted for her right wrist, tenor and baritone placed it on their left elbow, while the alto chose is left upper arm as preferred location. With the exception of the alto player, the other members reported a preference for having the actuator in direct contact with a bone. They felt the vibrations would “resonate” more in this position, probably because of bone conduction, hence producing a more

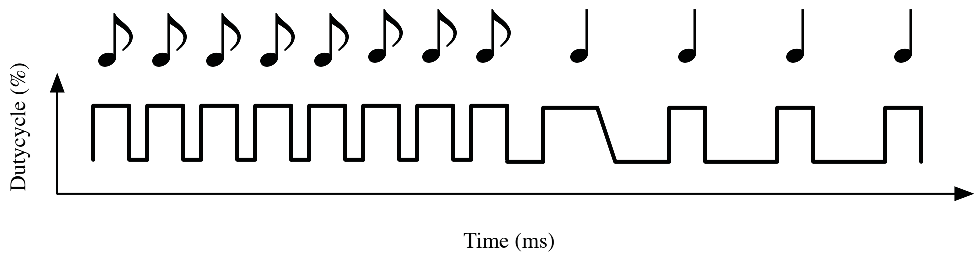


Figure 6.13: A representation of the tactile notification used to mark the ending of a movement. The metronome signal for the last bar of the movement would count the beats in eight-notes, and the usual pattern would be restored for the first bar of the new movement.

prominent vibration. The actuators were attached to the body by means of tight elastic bands, and they were concealed during the performance by the musicians' clothing.

For the performance, the stage at the *Gesù* was setup as illustrated in Fig. 6.14: the central node, placed behind the back row of speakers (see Fig 6.9b), was connected to the laptop running CLEF by means of a long Ethernet cable running from the stage to the theater's control room. Four Ethernet cables taped to the floor ran from the central node to the position each musician would occupy on stage. Upon their entrance on stage, the performers connected the loose end of the Ethernet cable to the actuator control units they were carrying. After each control unit connected, we performed a system check by remotely triggering each member's actuator, to which they responded by discreetly raising their hand.

6.3.3 Performers' Feedback

We recorded the comments and observation of Quasar's members during the rehearsal sessions that preceded the final performance, to keep track of their comments and remarks on the system, and document the learning process and integration of the tactile notifications into their rehearsal practice.

We conducted a total of six rehearsals throughout which the musicians' confidence with the system improved from a session to another. This was due to several factors:

- The technical solutions which we implemented following Quasar's indications — upbeat/downbeat differentiation, notification for ending of a movement, in-

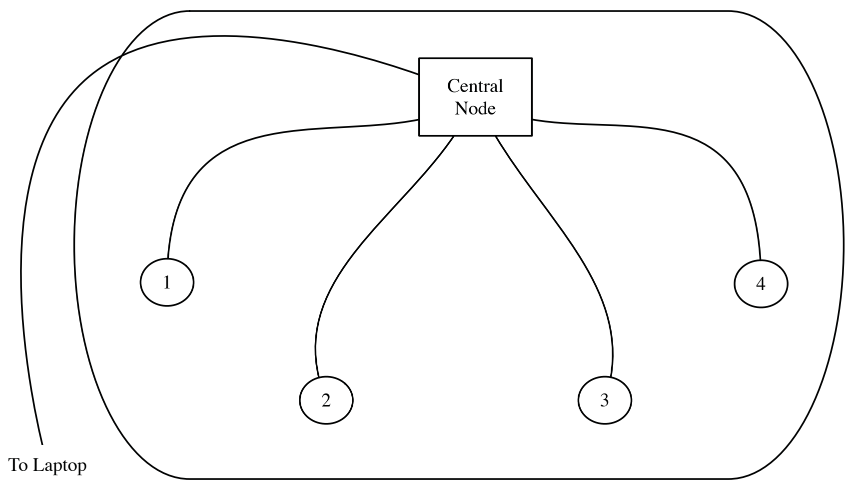


Figure 6.14: The setup of the tactile metronome system used for the performance.

creasing amplitude to compensate for adaptation effects — improved the overall transparency of the system.

- The performers' progressively got accustomed with the notifications and learned to direct their attention to the metronome signal; this process was made possible by the internalization of the piece's complex fingering, which for the first rehearsals was at the center of the performers' efforts.

The performers expressed their appreciation towards the tactile metronome system, emphasizing its more discreet nature and noninvasiveness when compared to regular auditory click-tracks. They stated that the piece could not have been performed without a metronome track, and that delivering tempo information via the sense of touch allowed them to pay more attention to the overall balance of the piece's soundscape. This last aspect was particularly appreciated: the tactile notifications *freed* the musicians' auditory sense, which would have been otherwise occupied by regular auditory click tracks, allowing them to focus on the music rather than on the metronome clicks.

Overall, Quasar expressed a high degree of satisfaction with the system which represented a viable and preferred alternative to on-stage auditory or visual feedback systems.

6.3.4 Composer's Feedback

In a questionnaire we submitted to composer F. Gran[11], we asked him to provide us feedback about his experience with the tactile metronome system. He confirmed that the availability of the tactile notifiers influence him in the composition of Champs Magnétiques, by allowing him to explore new rhythmical structures, as well as a non-conventional placement of musicians on stage.

When asked to compare our system to auditory click tracks he stated: *"One obvious problem with auditory click tracks is [...] that they sometimes can be heard also by the audience, especially at soft dynamics. I also think the auditory perception for the musicians can be disturbed with auditory click tracks, especially while performing softer dynamics and sensitive phrases. In this piece for example, the use of delicate multiphonic sounds with pulsating rhythms is very dependent on [the fact] that the musicians can constantly hear the details of the sounds produced in their instruments. Putting a click track in headphones would block the listening path."*

Overall, he expressed an interest of working again with such a system, and expanding the vocabulary of tactile effects available via the notifiers, to convey a broader range of information, especially in the context of live-electronics performances. At the time of writing, the composer is currently working on a new version of the piece, which could be performed with an extended version of our current system.

6.4 Conclusions

In this Chapter we presented examples of our work in the design of tactile notifications for music performance and musical practice, with particular emphasis to the evaluation and development of a metronome system for ensembles.

In the first Section we reported our results in the design and evaluation of tactile notifications for the interaction with a live-electronics system: the CIRMMT Live-Electronics Framework (CLEF). Several notifications were implemented to convey information about the start of a new Section in a CLEF piece, and to continuously monitor the internal state of one of the CLEF DSP modules. The performer involved in the evaluation positively rated his experience with our tactile notification system, particularly

[11] Full questionnaire available in Appendix A

for the case of a tactile metronome track which accompanied one of the pieces designed for the evaluation.

In the second Section we present a perceptual evaluation of a tactile metronome track, by comparing it to a regular auditory metronome. Results show that a tactile metronome performs equally well in cuing a musician to follow a target tempo, but reaction time to the metronome ticks is slower in the tactile modality.

Given the positive results obtained in the previous Sections, we developed a multi-user metronome system to be used in ensemble performance, which we described in the third Section of this Chapter. Composer F. Gran composed a piece for the Quasar Saxophone Quartet, to be performed with our distributed tactile metronome system. Several notifications were implemented together with the metronome track, directly issued from the musicians' feedback. The piece was successfully performed in a public concert and both F. Grand and Quasar highly rated their experience with our tactile notifications.

Overall, this Chapter showed the design process and implementation of stand-alone interfaces delivering tactile notifications to on-stage musicians. The results indicate that such systems can provide musicians with important cues, especially in the case of interaction with a live-electronics system.

Chapter 7

Conclusions and Future Work

7.1 Contributions

Designing systems that are capable of conveying complex but transparent information to a user via the sense of touch is a difficult task, whose success rests on the consideration of several key factors: the perceptual properties of the sense touch, both from a temporal and spatial point of view; the physical properties of actuators and their perceptual counterparts; and the in context, user-feedback driven design and evaluations of tactile interactions. The main contribution of this thesis is to propose a systematic approach toward the development of vibrotactile interfaces for music performance and practice, which is guided and informed by an analysis of these key factors.

We started our presentation with the definition of a framework for haptic interaction in music performance. First of all, we distinguish between two categories of haptic communication: *feedback* and *stimulation*. While feedback refers to the response of the interface to a user's direct action, stimulation generally indicates the communication via tactile cues of information that has not necessarily a direct link to a user's actions.

Feedback and stimulation can be delivered via two classes of interfaces: Digital Musical Instruments (DMIs) and stand-alone interfaces. We showed examples of design of tactile interactions for both these devices and provided an abstract model of tactile interaction in this context, which is presented in Chapter 2.

Subsequently, we presented a taxonomy of applications of vibrotactile feedback and stimulation divided into three main categories: 1) *tactile notification*, 2) *tactile translation* and 3) *tactile synthesis*. Each of these categories describes a very different function that tactile feedback and stimulation can achieve in an augmented interface:

1. Tactile notifiers provide users with information about their direct interaction with a system, or about the internal state of the system itself. A straightforward example in the music domain is a tactile stand-alone interface notifying the user of the successful activation of effects via on-stage controllers such as foot pedals or switches.

2. Tactile translation describes sensory substitution and tactile rendering techniques aimed at characterizing and modeling vibrations onto external structures or devices. Several examples exist in the musical domain of vibrotactile interfaces to translate music into vibration, or to model the vibrational behavior of an acoustical instrument onto a DMI.

3. Tactile synthesis describes the creation of abstract languages of tactile effects or icons to be delivered via tactile-enabled displays. Temporal or spatial vibration patterns can be mapped to external information by means of meaningful icons, or by an arbitrary association between symbolic icons and external sources of information.

The literature review presented in Chapter 2 reveals a very diversified range of actuator technologies embedded in vibrotactile devices for musical interaction. In Chapter 3 we presented techniques to mechanically characterize the properties of several of these actuators, namely ERMs, LRAs and voice-coils. We showed that these properties can affect the behavior of the actuator itself and this characterization allowed us to argue that each type of actuator presents advantages and disadvantages that make it more or less suitable for a specific application: Voice-coils present greater flexibility in terms of amplitude and frequency control, but their response needs to be characterized and compensated for and more complex circuitry needs to be implemented deploy them in large arrays; ERMs, on the other hand, present a more limited control — with amplitude and frequency output inherently coupled — but their cost and simpler driving electronics allow for an easier large-scale deployment.

In the following Chapters we presented our results in the development of applications for each of the categories we proposed in our taxonomy.

- Chapter 4 presented the use of voice-coil actuators for tactile translation techniques. We presented examples showing how tactile translation can be used to: improve the interaction with the haptic model of a bowed string; investigate the quality of the rendering of the vibrational behavior of an acoustic instrument; and use frequency compensation techniques to simulate the behavior of a vibrating structures and deliver musically relevant cues.

- Chapter 5 addressed tactile synthesis and its applications to the domains of media arts and music. We presented results we achieved in the development of hardware and software to be used in the implementation of tactile augmented garments and in the design of haptic effects to be delivered by them. These garments were used for the performance of *Ilinx*, a multi-sensory art installation, for which we developed a vocabulary of tactile effects to accompany sound and visuals. Subsequently, these garments served as tools to investigate the feasibility of developing abstract tactile icons to convey score information to musicians. We worked on the icons' design and evaluation in the context of *Musicking the body electric*, a multidisciplinary project aiming at developing a wearable score for mobile musicians.

- Chapter 6 proposed the design and evaluation of tactile notifications for music performance, focusing on the development of a multi-user tactile metronome system for ensembles. We provided details on the hardware and software design, as well as an evaluation of our system. A piece specifically composed for our tactile notification system was performed by the *Quasar* saxophone quartet in a public concert. The composer and the musicians involved in the project enabled us to perform a real-world validation of the effectiveness of our tactile effects.

7.2 Limitations and Future Work

The tactile rendering techniques proposed in Chapter 4 could be further explored. The augmented handle we designed for the *Phantom Omni* force feedback device could be effectively used to model the real-world vibrations of a violin bow. An evaluation of the rendering of these vibrations should be conducted to evaluate their perceived quality when the handle is manipulated by expert musicians. Similar considerations apply for the guitar vibration rendering, for which a more convincing simulation of the high frequency vibrations should be produced. This could be achieved by improving the rendering of attack and decay times. The use of a different actuator may also be considered. The vibration along the three different axis should be measured and dimensional reduction techniques could be used to map the three-dimensional data onto the actuator's longitudinal axis. In terms of experimental design, an *ABX* method could be used to compare stimuli. This would have the advantage to not rely on participants' internal model of a fake or real plucks. Once a better rendering achieved, this tool could be used to investigate the salient tactile cues perceived by a player on the neck of an acoustic guitar. The synthesized vibrations could be altered in order to be able to identify the effects of these modifications on the perceived qualities of the instrument.

The tactile synthesis and notification applications presented in Chapters 5 and 6 will be further developed and evaluated in the context of the continuation of *Musicking the Body Electric*, and in the performance of the revised version of F. Gran's *Champs Magnétiqus*, which is currently being produced. For the former project, in the next three years of development we will be able to observe the long term effects of learning and experience with the tactile display. The rehearsing and practicing over several months of the tactile icons delivered by the belt and the newly designed augmented garments will provide insights on the embodiment of this kind of language in music performance. Formal, longitudinal studies should be designed to track musicians' progress in performing with the tactile augmented garments. Moreover, their feedback should be collected to inform the design of new effects and icons. An investigation should also be conducted among the composers that will be progressively involved in *Musicking the Body Electric*, to determine preferred mapping strategies between score information and tactile icons.

For the revised version of *Champs Magnétiques*, a multi-site tactile display could be implemented for assigning different notifications to separate body-parts. This solution had already been discussed with the composer and the *Quasar* quartet, and could provide us with further insights regarding the possibility of simultaneous communication of several tactile cues. From a technical point of view, the multi-user tactile notification system could benefit from the development of a wireless transmission system for each of the metronome units. Given the time-critical context of our application, accurate timing of each one of the tactile metronome units should be guaranteed, as well as their synchronization. At the time of writing, we conducted preliminary tests in this sense, but latency and loss of information on the wireless communication channels have so far proven to be an obstacle for a functional implementation of a wireless system. To achieve this goal, a more thorough investigation of the possible technical implementations of wireless communication technologies should be undertaken in order to evaluate the effectiveness and feasibility of these solutions.

Appendix A

Questionnaires

A.1 Answers from Felix del Tredici after the performance of "40 Icons about Art/Music"

Q1) *How would you describe your experience with the belt in terms of its obtrusiveness (i.e. hindering your natural movements while playing)?*

A1) The belt is not obtrusive at all. Even less so in the full suit.it depends on the tightness, but in general I had no problems with anything movement-wise.

Q2) *In general, did you find the vibrations easy to perceive?*

A2) the vibrations were quite difficult to perceive towards the middle of the back area.

Q3) *What are your comments on the icons design? Were the icons easily perceivable and distinguishable?*

A3) icons were perfect. Could not think of a better system for the belt. Full suit is a different story.

Q4) *In the context of tactile interface development, an interface (such as the belt) is said to be "transparent" if it permits the communication of tactile icons with a minimal impact on the user's cognitive load. A transparent interface does not demand all the user's attention and does not hinder his/her capacity to perform a task.*

A4) I mean.... I think the nature of wearing something that tells you what to do is already non transparent. Of course if I am wearing something, and I know that it's actions will dictate what I do next, then it will take up a huge part of my brain. Fortunately, the piece was simple on paper, and I already knew what was coming next in some respects. So, that took the load off, but I would argue that if you wanted to make something that was transparent then the belt is not the way to go. It's not a bad thing, by the way. I'm just saying that the belt is there to paid attention to, right?

A.2 Answers from Fredrik Gran about the composition of Champs Magnétiques

Q1) *Were you influenced in your approach to the composition of Champs Magnétiques by the availability of a tactile metronome system?*

A1) Yes. I have worked with somewhat similar ideas for acousmatic works. The tactile metronome system made it possible to transfuse these ideas into writing for acoustic instruments. The metric and rhytmical ideas of the compostion, as well as the non-conventional placement on stage, was affected by the synchronisation possibilities with the system.

Q2) *Would you have composed Champs Magnétiques differently if it had to be performed using, for instance, auditory click tracks?*

A2) Yes. One obvious problem with auditory click tracks is the leakage problem, that they sometimes can be heard also by the audience, especially at soft dynamics. I also think the auditive perception for the musicians can be disturbed with auditory click tracks, especially while performing softer dynamics and sensitive phrases. In this piece for example, the use of "delicate" multiphonic sounds with pulsating rhythms is very dependent on that the musicians can constantly hear the details of the sounds produced in their instruments. Putting a clicktrack in headphones would block the listening path. In the first version of this piece the tactile notifiers are also almost constantly sending meter pulses. I imagine auditorty click tracks would be more annoying to keep hearing throughout the piece, while at the same time the performer tries to create music, also auditory. The tactile notifiers has another benefit of that they can be moved, or that one performer can have more than one notifier at different parts of the body to switch in between, which can clearly help to distinguish for example different sections of the composition.

Q3) *Would you work with such a system again?*

A3) Yes. As a start, I am making a revised version of the piece. I could also see the system being really useful when working with live electronics, as well as a further developed categorization of possible notifications (long, short, strong, soft, transforming etc) and the use of multiple notifiers per musician.

Q4) *Think about the context of a performance using a live-electronics system (like CLEF). Often a screen has to be placed on stage to give feedback to the musicians about what is happening in the piece. As a composer, what do you think of this situation?*

A4) I think it can vary from piece to piece. However, if for example the same feedback could instead be given to the musicians from tactile notifyers, it could not only exclude the sometimes disturbing visual aspect of having a screen on stage, but also hopefully make the feedback a more integrated and intuitive part of the actual performance. The tactile sense is already part of a musician performing an instrument; the feel of the string/ key etc.

Q5) *Do you think that vibrotactile cues could be used to convey other musically relevant information? Would such a technology could influence your approach to composition (especially with live-electronics)?*

A5) Yes. I think there are many relevant things possible to convey through vibrotactile cues. I can imagine many varied compositional ideas which could get influenced by it. And develop its usage.

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