Cutaneous Grooves: Composing for the Sense of Touch

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Abstract

This paper presents a novel coupling of haptics technology and music, introducing the notion of *tactile composition* or aesthetic composition for the sense of touch. A system that facilitates the composition and perception of intricate, musically structured spatio-temporal patterns of vibration on the surface of the body is described. An initial test of the system in a performance context is discussed. The fundamental building blocks of a compositional language for touch are considered.

Keywords

tactile composition, vibrotactile, music, multi-modal

Introduction

Certain kinds of music are often considered 'visceral', meaning that they exhibit some element relating to the body. Sometimes we even refer to music as being 'tactile,' usually in reference to its sonic texture or timbre. Why not take these metaphors a step further to actually materialize these visceral or tactile elements of music? There have been investigations along various musico-haptic lines, several of which have enlisted haptic devices as enabling technology for the creation of music. The approach taken in this paper views haptic technologies – in particular the vibrotactile stimulator – as independent output devices to be used in conjunction with the composition and perception of music. Vibrotactile stimuli are viewed not as signals carrying information per say, but as aesthetic artifacts themselves. This purely aesthetic approach to artificial tactile stimulation is a departure from much previous work in the field of haptics. A system that facilitates the composition and perception of intricate, musically structured spatio-temporal patterns of vibration on the surface of the body was designed and subsequently tested in a performance setting. Because sound is essentially vibration, the well-established field of music provides an abundance of analogies, technical guidelines, and inspiration for the newborn field of tactile composition as presented herein.

Background and Motivation

A search for ways to push the envelope of music lead the author to consider the coupling of music with other sensory modalities. A survey of multi-modal work involving music revealed a lack of efforts in the area of haptics, most of the work falling in the broad category of visual music. A review of the psychophysical literature on touch confirmed the feasibility of a tactile accompaniment to music or, as it is referred to herein, *tactile composition*. The skin is more remarkable and versatile than most of us know, capable of fine spatial and temporal analysis. This section is intended to briefly familiarize the reader with the skin's basic psychophysical parameters[1], with a focus on the vibrotactile response. It is vital for the tactile composer to have a good feel for these parameters, especially when working so close to the fundamental levels of a new medium.

The range of the skin's vibrotactile frequency response is roughly 20-1000 Hz, with maximal sensitivity occurring around 250 Hz. The skin is relatively poor at frequency discrimination, lacking the exquisite analysis mechanisms found in the ear. Reports on the frequency discrimination abilities of the skin are dependent on experimental paradigm and thus tend to vary. Sherrick proposes that the results suggest that between 3 and 5 values of vibration rate can be distinguished between 2 and 300 pps [6]. Rovan and Hayward report that ranges broadly divided into 8 to 10 discrete steps are perceptible over a range of 70 to 800 Hz [5]. The intensity range of the skin reaches about 55 dB above threshold of detection, beyond which vibrations may become unpleasant or painful [7]. A range of values for the just noticeable difference (JND) of intensity have been reported in the literature, the smallest (0.4 dB) reported by Knudson in 1928 and the highest (2.3 dB) by Sherrick in 1950 [7].

Prolonged tactile stimulation can result in adaptation, a decrease in the sensory magnitude of a stimulus. Sensation magnitude declines during the exposure to the adapting stimulus and then gradually recovers after the stimulus is removed; recovery time ranges from a few seconds to several minutes depending on the duration and intensity of exposure [7].

Of particular significance to tactile composition is the set of illusions collectively referred to as *apparent motion on the skin*. When tactile stimuli are sequentially pre-

[1] For an excellent synopsis of the psychophysics of touch, refer to Chapter One of the book *Tactile Hearing Aids*. [7]

sented to two distal points on the skin with the right timing, the stimulus is perceived to move rapidly from one point of stimulation to the next. A particularly salient illusion, in which a properly timed and distributed train of taps creates the illusion of a phantom tap 'hopping' between two or more points on the skin, is known as the *cutaneous rabbit effect* or *sensory saltation* [2].

Previous Work and Related Research

The work presented in this paper draws upon a number of fields. The growing study of *visual music* provides invaluable creative and technical guidance for tactile composition. From the early days of the color organ to the more recent phenomena of video mixing and digital music visualization software, the coupling of music and visual media has been explored in considerable depth. This field has seen significant leaps with improvements in display technology, a trend that will surely manifest itself in tactile composition.

One particularly relevant area of research within the haptics community is *sensory substitution*. This field examines the provision of environmental information through a human sensory channel different from that normally used and is largely concerned with the information processing capabilities of the skin. Studies on the tactile communication of speech and the design of tactile hearing aids provide unique insights into the interrelationship of audition and touch.

The entertainment industry has seen various attempts at integrating the sense of touch with visual and audio media. One example is the puffs of compressed air against the ankles or necks of unsuspecting audience members found in theme park movie rides. It is increasingly common to encounter vibrotactile feedback in video-game controllers. There have also been isolated efforts aimed at presenting music to the body, one such effort utilizing a waveguide to directly couple musical vibrations to the skin [8]. One performer uses powerful sonic vibrations to deliberately resonate specific body parts of the audience.

Sound and touch have a relationship that dates back to the origins of music. There have been a number of studies on haptic feedback for the musician, several of which view haptic and tactile devices as enabling technologies for the creation of music [4],[5]. Such investigations provide useful lessons on the application of haptics technology in a musical context.

System Design

A system that facilitates the composition and perception of intricate, musically structured spatio-temporal patterns of vibration on the surface of the body was designed. At the heart of the system is a full-body vibrotactile stimulator comprised of thirteen transducers worn against the body. In this section, several key factors in the design process are discussed.

Why vibrotactile?

A number of tactile stimulation devices are available, each of which stimulates a specific tactile response. These include pressure, thermal, slip, electrocutaneous, and vibrational displays. The vibrotactile modality was chosen for two reasons. First, vibration devices are generally easiest to work with and in particular, to control. Second, the bandwidth of the skin's vibrotactile response coincides most closely with that of music.

Transducers

Because they are inexpensive, compact, and easy to control, pager motors were initially considered as transducers. However, they tend to operate in and on/off manner, usually vibrating at a set frequency. A primary specification for the transducers was versatility with regard to output waveform. The transducer chosen for the first version of the system was the V1220, manufactured by Audiological Engineering for use in their line of tactile hearing aids. The V1220s are compact as shown in Figure 1(a). They have a coil-based design and can thus be driven with any waveform in the tactile frequency range. They produce very clean, localized vibrations, have a relatively high power output, and exhibit a frequency response that peaks at 250 Hz. The requirement that they be worn close to the skin, however, makes them somewhat impractical, since clothing frequently presents too much impedance for the transducers to be effective.

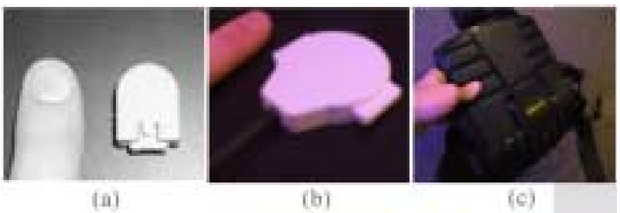

Figure 1. Transducers used in system.

(a) V1220; (b) modified flat speaker; (c) Interactor

The second version of the system used a predecessor to the V1220 as illustrated in Figure 1(b). This transducer is also coil-based, but has a simpler design. Specifically, the transducer is made by attaching a weight to the center of a 40mm flat speaker and enclosing it in a small plastic case; this modification serves to lower the resonant frequency of the speaker into the tactile range [Franklin, personal communication]. Although they have a larger surface area contacting the skin and consequently do not produce as localized a sensation as the V1220s, they are more powerful (partly due to spatial summation in the skin) and can penetrate clothing more effectively. Manufacturing a set of these transducers with a consistent frequency response has proved to be a difficult problem; center frequencies fall in the neighborhood of 350 Hz. Future versions of the device will likely employ the V1220s and require the user to wear the transducers directly against the skin.

The perceptual and compositional importance of low-frequency vibrations was realized midway through the design process. Accordingly, a low-frequency transducer was added to the system. The Aura Interactor, a backpack-like wearable intended for use with video games, was chosen. The device is shown in Figure 1(c) and consists of a woofer mounted inside of a hard plastic case.

Transducer Placement

There are thirteen transducers in the device: twelve high-frequency and one low-frequency. The number of transducers was limited by the control hardware used; future versions of the suit will likely contain more than thirteen channels. It should be noted though, that the compositional and perceptual value added by increasing the number of channels eventually levels off due to the diffuse receptive fields of some mechanoreceptors in the skin. For the following discussion, please refer to Figure 2, which illustrates the transducer distribution on the body.

Three main principles guided the situation of the high-frequency transducers. First, it was decided early on to distribute the transducers across the entire surface of the body. This decision was motivated by the analogy of a dancer, whose compositional tool is essentially the entire body. Three transducers are distributed roughly evenly along the length of each limb. The middle transducers on the arms and legs were placed, respectively, just below the elbow and knee creases for comfort and ease of movement. Second, each transducer was positioned as close to glabrous (non-hairy) skin as possible. Glabrous skin contains more receptors than hairy skin, making it more sensitive to stimulation. The thigh transducers are the exception; they were placed on top rather than below the thigh for increased comfortability while the user is seated. Third, due to skeletal leakage of vibrations into the ear – resulting in undesirable sonic artifacts – no transducers were placed on or near the head. A transducer located on the nape of the neck was considered, but rejected for this reason.

The low frequency transducer is situated against the lower back. It seemed intuitive to present low frequency vibrations to the torso, as this is generally the region of the body in which one experiences powerful low frequency vibrations at a club or concert, for instance.

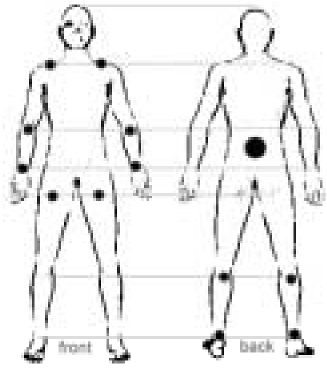

Figure 2. The small black circles represent the high-frequency transducers. The large circle on the lower back represents the Interactor.

Wearable design

When working with vibrotactile devices, it is essential to maintain a tight interface between the tactor and the skin. Elastic straps with Velcro were used toward this end; in addition to providing the necessary pressure, they are inherently adjustable. The first version of the suit required the user to strap on each transducer individually. The shoulder transducers were held on via a harness-like contraption and the Interactor was strapped to the back of a Herman Miller chair (which was chosen for its low-impedance mesh backing). In version two of the system, all of the transducers and wires were embedded in a nylon suit as shown in Figure 3. A one-size-fits-all design was required, so the suit was designed to be loose fitting, with external elastic straps at each transducer point. An elastic shoulder harness, which could be adjusted by pulling down the straps located just above the breasts, was sewn into the suit to secure the shoulder transducers. The Interactor is held against the lower back by two adjustable belt straps that wrap around the torso. The outer cover of the device was removed to reduce the weight load. The transducer wiring was routed through channels running along the lengths of the arms and legs and down the back, and exits in the form of a tail. A tail was chosen over an umbilical chord because it hangs from the suit more naturally.

Figure 3. Second version of the vibrotactile suit.

During initial experimentation with the system, the perceptual quality of the vibrations was found to be dependent on the pressure of the transducer against the body. Specifically, when the strap is relatively loose and the transducer rests comfortably against the skin, the vibrations are perceived superficially on the skin. Tightening the strap couples the vibrations to the bone structure, resulting in a deeper, more diffuse sensation. The latter is undesirable because the vibrations are less isolated (due to skeletal conduction) and excessive tightening of the straps often impedes circulation.

Control

The transducers are controlled via a Protools Digi001interface. The Digi001 is a multi-channel digital audio hardware interface that performs the D/A conversions necessary to drive the transducers. Each Digi001 output is independently amplified and sent to one transducer. While the signal quality is admittedly overkill for this application, the Digi001 package was chosen as a quick solution as well as for its versatility, extensibility, and strong support base.

Composition Environment

Protools, a standard MIDI and digital audio sequencing environment for the Macintosh, is used to compose for the suit. The software is configured so that each audio track is routed to a specific transducer. Because the Protools interface was not designed for this type of application, composing with it is painstaking. The author has developed some useful techniques using MIDI to speed up the process, but it remains awkward. The benefit of working in ProTools though, is the ability to compose the music and tactile components in parallel within the same environment. Before the full potential of the tactile medium can be realized, better compositional tools must be designed.

Real-time Control

A MAX/MSP application was designed that allows a user to control the suit in real time for use in a performance context. Essentially a "tactile sampler", this application allows a user to send preloaded samples to the suit using the Macintosh keyboard as a controller. The application includes a saltation module that allows a user to configure and trigger saltation patterns in real time as well as a pattern generator, which can play back precomposed patterns onto the suit.

Audio Presentation

Presentation of audio through headphones was determined to be optimal for two reasons. Practically, the headphones help to isolate the music from transducer noise. In addition, the phenomenon of internalization, the perception of sound to originate from within the head, increases the 'overall intimacy' of the experience; both the audio and tactile components of the composition appear to originate on or from within the body. The overall experience – in particular the observer's sense of space and the interaction between the tactile and audio elements – is markedly different when the music is played through loudspeakers.

A Compositional Language for the Sense of Touch

It is indeed premature to hammer out the details of a language for tactile composition. It seems more productive at this point in time to identify the *underpinnings* of such a language, specifically those dimensions of tactile stimuli that can be manipulated to form the basic vocabulary elements of a compositional language. Because tactile stimuli are viewed as aesthetic artifacts, the interpretation of psychophysical parameters made herein differs from those found in other haptic disciplines such as sensory substitution.

Frequency

Geldard points out that the correspondence between vibratory frequency and perceived "pitch" is a tenuous and uncertain one. Vibratory pitch proves to be a joint function of both frequency and amplitude [1]. Due to the poor frequency analysis abilities of the skin, frequency will not assume a first order dimension of composition, as it does in music. Subjects in psychophysical experiments have reported a sensation of periodicity or buzzing at low frequencies (below 100 Hz) while at higher frequencies a more diffuse, smooth sensation is perceived [7]. Taking this into account, frequency will represent a more qualitative dimension for tactile composition.

Intensity

Tactile composition calls for a continuum of intensities ranging from threshold of detection up to the limits of discomfort. Dynamic articulations – from the accent to the crescendo – are an important aspect of tactile composition. A dynamic balance or, as referred to in the recording studio as *a mix*, will come into play as multiple compositional strands are layered in space and time on the skin.

Of particular utility is the amplitude envelope of tactile stimuli. The attack and decay of a tactile event can be varied to create a wide range of perceptual effects. For instance, an abrupt attack will be perceived as a sudden tap against the skin whereas a more gradual attack seems to rise up out of the skin. By applying subtle variations to the attack and decay of stimuli, it is possible to generate a continuum of sensations between these two extremes. Based on the author's experience with tactile composition, envelope manipulations will assume a salient role in tactile composition. This hypothesis is supported by a study by Gescheider *et al*. in which the best intensity discriminations were made when an intensity increment was imposed upon a continuous background 'pedestal' of vibrations [7].

Duration

Vibrotactile stimuli of duration less than 0.1 seconds are perceived as taps or jabs against the skin, providing the tactile equivalent of musical staccato. Longer duration stimuli with gradual attacks and decays, on the other hand, may be used to construct more smoothly flowing tactile phrases. Differences in duration provide an important means of grouping tactile events when layering multiple voices on the same area of skin. In addition, stimulating an area of skin for an extended period of time can result in adaptation, which may be harnessed compositionally to ease a part into the background.

Waveform or Spectral Content

Due to the skin's poor frequency analysis abilities, subtle variations in spectral content cannot be perceived in the way timbre is by the auditory system. The haptic system is, however, able to recognize the qualitative differences between say, a sine wave and a square wave presented to the skin, perceiving them respectively as smooth and rough. The vibrotactile gamut from pure sine tone to frequency-rich spectrum to noise is characterized as a continuous transition from smoothness to roughness [5]. For tactile composition, waveform can be correlated to the "texture" of tactile stimuli, as in music.

Space

As far as our spatial senses go, touch comes in second after vision. The location and relative positioning of tactile stimuli on the body surface will assume a first order dimension for tactile composition, representing the closest analogue to musical pitch. Of particular compositional value with regard to space is the class of phenomena known as apparent motion on the skin. When applied over relatively large areas on the body surface, apparent motion can result in some extremely vivid sensations ranging from a miniature rabbit (of the cutaneous species) darting up the arm to smooth waves of vibration washing over the body from shoulder to toe. Different patterns of apparent motion may be sequenced and layered, resulting in a synergistic sum of movement on the skin.

In addition to being grouped – by composer and observer alike – on the bases of rhythm, dynamics, duration, and envelope, tactile phrases will be grouped spatially, with the body acting as a stage of sorts on which a vibrotactile dance unfolds.

The Massager Misnomer

The most salient analogy in people's minds when they encounter a device that produces vibrations against the body is none other than the personal massager. What are massagers designed to do? Relax you. There is in fact an entire field of medicine called *vibrational therapy* that applies vibrotactile stimulation in a therapeutic context.

On the other hand, the compositional approach to vibrotactile stimulation taken in this paper encompasses a wide spectrum of emotive content. Part of the emotional potency of the tactile composition comes from its ability to enhance, intensify, and expand the preexistent emotive elements of music. In addition to modulating the a priori affective response to music, the tactile composition can stand on its own as an emotionally potent compositional medium. Because sound is essentially vibration, tactile composition shares many of the fundamental elements which give rise to the emotional potency of music. According to Pratt, if an emotion is to be real, the organs of the body, and in particular the viscera, must be made to vibrate (1952). In the case of tactile composition, we actually go a step further than music by putting the composition *on* the body. A detailed analysis of the affective response to tactile composition is premature and beyond the scope of this paper.

Cutaneous Grooves: A Concert for the Skin

During September 2001, a series of concerts was held to introduce tactile composition to the greater MIT community as well as to test the technology and hypotheses presented in this paper. The concert was as much an experiment as it was an artistic event. A space was set up at the MIT Media Lab in which ten audience members at a time, each equipped with their own full-body vibrotactile stimulator, experienced a one hour concert of music and tactile compositions. The pieces comprising the concert are briefly described in order to give the reader some insight into the compositional process.

Two of the pieces in the concert were soundscapes composed by the author. To build suspense, the first piece opened with a minute of just audio, including a vocoded passage on the anatomy of touch. It then imitated the sound and feel of a heartbeat and the flow of blood down the limbs. The other soundscape began with a purely tactile introduction (no music), with white noise played to mask the transducer noise, and transitioned into a three minute simulated thunderstorm. Audience members reacted strongly to the thunderstorm; it was a nice demonstration of the synergistic sum of a simple vibrotactile pattern and a more complex piece of audio.

One musical selection[2] consisted of simple repeating percussive patterns layered over one another. The tactile

[2] "Purus River" from the Philip Glass album *Uakti*

accompaniment was an attempt at translating this compositional idea to the body. In particular, it demonstrated the notion of selective attention on the skin; that when simultaneously phrases are grouped spatially or by other means, the observer can selectively attend to each phrase as one can tune in to different voices while listening to a piece of music. By highlighting different parts of the music with the tactile accompaniment – bringing some into the foreground and others into the background – the audience's attention could be focused on different aspects of the music.

For two of the pieces, the music and tactile components were written simultaneously. By engaging in this kind of parallel or multi-modal composition, the author was able to explore the interplay between the two composition processes. It was indeed a two-way street, with the music composition often influenced by a certain tactile idea and vice-versa. These pieces also explored the interrelationship between the musical and tactile components. They need not always mirror each other; they are independent compositional strands and can coexist in a number of ways ranging from rhythmic unison to *cross-modal counterpoint*.

Much technical knowledge was gleaned from holding the concerts. More interesting, though, is the feedback received from the audience about the experience, which confirmed many of the author's initial hypotheses surrounding tactile composition.

An equivalent of the psychological notion of expectation found in music was experienced by audience members on the skin. Specifically, when a pattern was repeated for some period of time, audience members expressed surprise at any variation or straying of the pattern. Several audience members noted that at certain instances it actually felt as if the tactile stimulations were making them move. One audience member who was a drummer claimed that it gave him a sensation similar to that of playing the drums; where different body parts are rhythmically moving in an orthogonal fashion.

There were consistently strong reactions to larger patterns in the composition that spanned the entire body, such as saltatory vectors that rapidly swept from head to toe. Audience members often reported that at first it was difficult to make sense of what was happening on their skin, but that even during the brief duration of the show, their ability to comprehend and appreciate the compositions improved.

As a testament to affective interactions between the two mediums, one audience member reported that if the music was calm and soothing, then the tactile patterns felt even more so, whereas if the music was dissonant or jarring, the tactile patterns made him feel on edge, almost uncomfortable.

Future Directions and Potential Implications

Tactile composition can stand on its own as a viable compositional form. Thus it is hoped that this new medium will provide artistic opportunities for hearing-impaired individuals. Experiments aimed at the tactile augmentation of movies are underway, bringing us one step closer to the Feelies of Huxley's *Brave New World*. Other plans include the automation of the music-to-touch translation, allowing one to use digital audio as input and to experience a real-time tactile interpretation of music – analogous to the colorful visualization plugins packaged with software MP3 players. As the medium becomes more established and widespread, it will also be interesting to see how – if at all – musical thinking will be affected. Of course it is speculative, but perhaps as people begin to think in tactile terms, their approach to both music composition and listening will be altered, ultimately pushing the field of music in new directions.

The system presented herein may be construed as a new tool for the tactual visualization of music; it is certainly that, but goes much deeper. The Cutaneous Grooves project is just the beginning. With the first tools in place, we can begin to explore the compositional universe of the tactile medium.

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