RippleTouch: Initial Exploration of a Wave Resonant Based Full Body Haptic Interface

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ABSTRACT
We propose *RippleTouch*, a low resolution haptic interface that is capable of providing haptic stimulation to multiple areas of the body via a single point of contact actuator. Concept is based on the low frequency acoustic wave propagation properties of the human body. By stimulating the body with different amplitude modulated frequencies at a single contact point, we were able to dissipate the wave energy in a particular region of the body, creating a haptic stimulation without direct contact. The *RippleTouch* system was implemented on a regular chair, in which, four base range speakers were mounted underneath the seat and driven by a simple stereo audio interface. The system was evaluated to investigate the effect of frequency characteristics of the amplitude modulation system. Results demonstrate that we can effectively create haptic sensations at different parts of the body with a single contact point (i.e. chair surface). We believe *RippleTouch* concept would serve as a scalable solution for providing full-body haptic feedback in variety of situations including entertainment, communication, public spaces and vehicular applications.

Author Keywords
Haptic interfaces; Full Body Haptics; Acoustic wave propagation

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation: User Interfaces: Haptic I/O

INTRODUCTION
Haptic interfaces plays an important role in modern human computer interaction. From simple vibrations of a mobile phone to a complex rendering of cutaneous and kinesthetic feedbacks in a tele-operating robot, haptic interfaces helps to make interactions with devices more intuitive and expressive. Vibro-tactile haptic cues are perceived through the *mechanoreceptors* on the skin. Being the largest organ of the human body, skin provides a multitude of possibilities and space to design haptic interfaces. Other than few exceptions (such as [11, 19]), for cutaneous sensation to be perceived, relevant point of skin must be stimulated by separate actuators. A user would have to either touch these actuators directly ([10, 17, 6]) or they can be embedded into a wearable form ([3, 22]).

In this paper we introduce a low resolution haptic interface, *RippleTouch*, which utilizes low frequency acoustic wave propagation properties in human body to create a haptic actuator which can stimulate multiple areas of body with a single contact point. *RippleTouch* uses a dual tone, amplitude modulated, low frequency acoustic waves to match the resonance frequency of tissues in different parts of the body. By carefully selecting frequencies, wave energy can be made to dissipate in specific regions of the body so that a user perceives a cutaneous sensation on respective areas. The current version of the *RippleTouch* prototype uses four base range speakers

Figure 1: RippleTouch: single contact point full body haptic display. A user pointing to the location of tactile sensation in the body, which was actuated using a speaker system embedded in the bench

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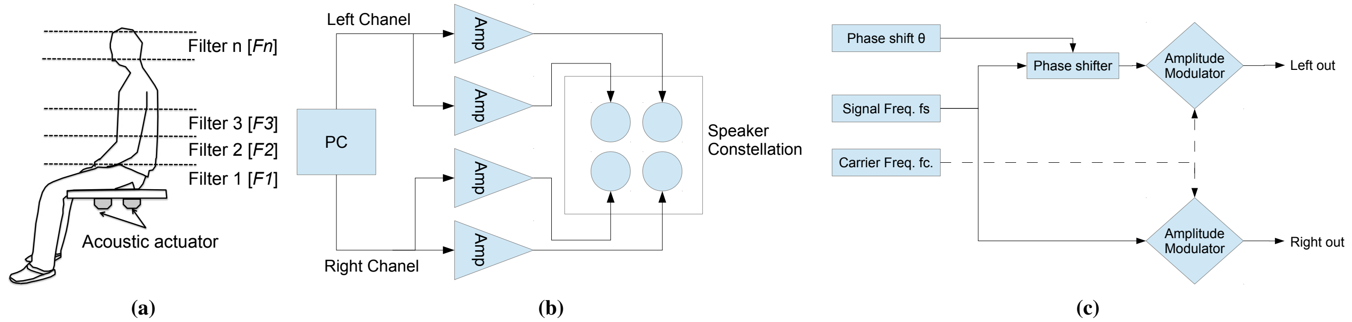


Figure 2: a) Analogy of human body as a set of cascading filters for acoustics, b) Connection Diagram from an audio interface to base range audio actuators, c) Block diagram of the haptic signal synthesizer.

mounted in the seat of a chair and driven by a simple stereo audio interface.

Key features of the proposed systems can be summarized as follows:

- *Single point of contact*
  RippleTouch only need a single point of contact, a user does not need to wear complex actuator arrays and does not need to keep in contact with multiple actuation points. This removes significant amount of physical constraints, making it easy to deploy more practical haptic interfaces in public spaces such as movie theaters (i.e. wearing special equipments are not necessary before entering the cinema).

- *Reduced complexity*
  Haptic feedback systems with high number of independent actuators are difficult to design and deploy as the electronics and other hardware integration becomes very complex. Furthermore, synthesizing haptic signals for each independent actuator and synchronizing them does not scale. In contrast, *RippleTouch* can be driven using a typical stereo signal (available in any PC) with four actuators located in a single contact point. This significantly simplifies the complexity and connectivity of the hardware and software implementation.

- *Easy integration*
  RippleTouch mostly uses inaudible frequencies in the low end of the acoustic band. Therefore, *RippleTouch* can be integrated into existing media such as movies and computer games and be driven by the same audio interfaces.

RELATED WORK

Information transmission through vibro-tactile systems has been studied through many different techniques. Information can be coded temporally, spatially or combination of spatio-temporal simulations. In the context of the proposed system, background of spatial tactile stimulation on the skin is discussed in this section.

Skin utilization on spatio-tactile interfaces can be done in many different ways. An array of actuators can be concentrated on a sensitive area on the skin [4], or individual actuators can be distributed in different parts of the body [7]. Concentrated actuator arrays are generally intend to make a high resolution haptic display which can render complex information such as static 2D images [17, 2], 3D shapes [12, 15, 18] and dynamic information such as motion [9, 13]. In order to represent complex information on a tactile display, a high concentration of actuators are necessary, and also, in most cases each actuator should be controllable individually. Number of actuators adds constraints on the hardware design, such as form factor, usability, price. Furthermore, higher number of actuators needs complex electrical and software design. Therefore, many modern designers utilize indirect ways to optimize the number of actuators to fit the requirement of the application. Widely used perceptual illusions includes Phantom sensation [1] where imaginary actuators can be simulated with proper temporal simulations and Apparent motion [5] where continuous stroke like motions can be simulated using discrete actuators. For example, Israr et. al. presented an empirical based model to properly simulate Phantoms and Apparent motion using an optimized actuator array [10]. However, scaling of such illusions to a large area has not been successful without increasing the number of actuators. Even though, out of the focus of this paper, tactile illusions such as Cutaneous rabbit might shed a light on scaling the haptic illusions to larger area on the body [8].

Haptic interfaces which are relatively in low resolution but spread across a wide area of the body are used in practical applications such as games (e.g. TN Games wearable haptic jackets [1]) and automobiles [6]. In addition, previous research has confirmed the humans ability to understand coded information via distributed actuators in different part of the body [7, 20]. Such devices are built with multiple spatially spread actuators that are in contact with different parts of the user's body. Actuators can either be placed in an object where users comes into contact such as a chair [6, 16] or it can be a wearable actuator array [3, 21, 22]. Distributed actuators also need to address the issues such as keeping proper contact with the skin, controlling multiple independent actuators, etc. Furthermore, with distributed actuators, user perceive the sensation as isolated event because the stimulation is highly localized.

In this paper we describe a single contact point haptic interface which can stimulate different parts of human body using the properties of acoustic wave propagation. Proposed

[1] `http://tngames.com/products`

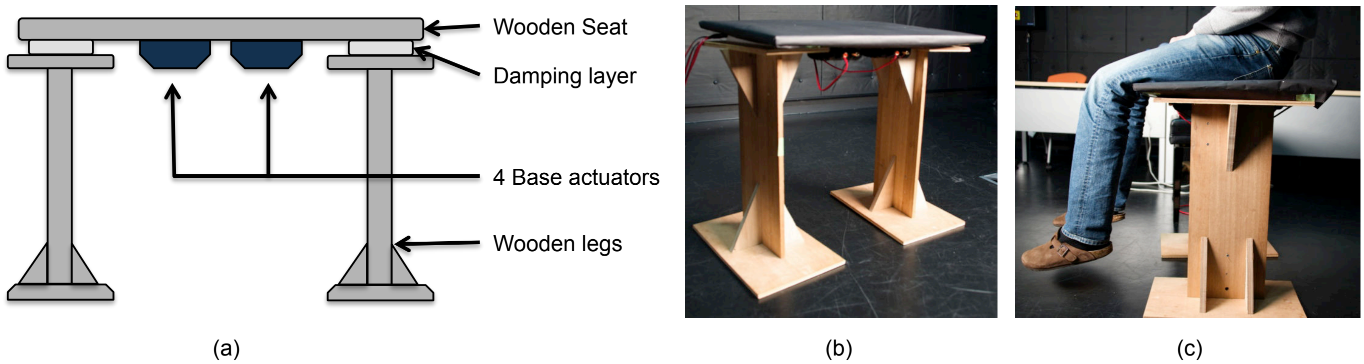


Figure 3: First Prototype of *RippleTouch*. (a) Actuator placement and chair design. (b) Real prototype setup on a bench. (c) A user sitting on the bench)

system uses an audio speaker based actuator which can be placed on a seat and with proper application of audio signals, user can feel the cutaneous sensation on different part of the body. Furthermore, lack of energy concentration makes the sensation perceived to be fairly homogeneous.

CONCEPT

Haptics are classified into two fields relative to the nature they are sensed by humans. *Cutaneos* (vibrotactile) which can be felt through the skin and *kinesthetic* (force feedback) which are sensed using the motion and pressure in muscles and tendons. In this paper, we primarily focus on cutaneous feedback. Different parts of the skin carries different characteristics of sensitivity to haptic cues. Given the large size of the sensing area, different methods are used to utilize the skin as a haptic input. Commonly used strategy is to concentrate the actuators on the most sensitive areas of the skin so that high information rates can be achieved. Another technique is to utilize inherent phenomenon of the human sensing system such as perceptual illusions; i.e. phantom sensation [1], apparent motion [5].

Similar to any object, human body can act as a transmission line for acoustic waves. Certain acoustic frequencies pass through the body and some get absorbed (filtered) by the body. Some of this absorbed energy is dissipated as mechanical vibrations of our body tissues, bones and organs. Since our body is non homogeneous (consist of hollow cavities, rigid bones and soft tissues), different parts of the body have different wave propagation characteristics with different resonant vibration frequencies. Thus the major frequencies absorbed in different parts of the body can be differentiated. Hypothetically, if we are to imagine a person sitting on seat as shown in Figure 2a, we can define imaginary horizontal layers of the human body, which acts as a set of cascading filters with transfer functions, $F_1(f)$, $F_2(f)$, $F_3(f)$, ... $F_n(f)$ to the acoustic signals exerted by upward mounted speaker at the bottom. If we are to assume, each layer has resonant frequencies f_1, f_2, f_3, ... f_n, and if $f_1 \neq f_2$ and $f_2 \simeq F_1(f_2)$, then by operating speakers at frequencies f_1 and f_2 we will be able deliver wave energy to first and second layers of the body separately.

However, above mention scenario is far from the real case. In reality, human body has many different routes for acoustic waves to travel and also signal characteristics of body depends on the person. Therefore, the functions for each layer is complex and highly subjective. However, our hypothesis is that we can find a number of layers in the human body which can partially sustain the above mentioned relationship for a given set of frequencies. Goal of *RippleTouch* is to examine the possibility of existence and classify the acoustic frequencies that can distinguishably vibrate separate parts of the human body.

Initial explorations are conducted within the research team to understand plausible set of frequencies and other parameters which are important to simulate resonant on human body. Based on the observations, effective range of frequencies for the vibrotactile stimuli should be in the range 1 to 20 Hz. However, these frequencies are out of the bandwidth of the general purpose audio equipments. Therefore, we used an amplitude modulation scheme with carrier frequency ranging from 30 to 90Hz. All the waves are sinusoidal waves. Figure 2c shows the block diagram of the audio synthesis system. A phase shifter is used in one channel to study the effects relative phase changes between two sides of the body.

IMPLEMENTATION

In order to evaluate the possibility of making an acoustic resonant based haptic interface, we implemented a prototype system as shown in Figure 3. This prototype consisted of a chair surface that is used as a single point of contact for low frequency acoustic waves. Chair surface and legs are made from plywood. A damping layer is introduced between the surface and the legs to prevent acoustic energy loss through legs. In the current prototype, chair surface is kept flat and rigid to maximize the contact between the user and the surface for optimal acoustic wave traversal. Top surface of the chair has a soft material to add some comfort without significant attenuations.

Four Aura AST-2B-04 (4 Ohm, 50W) base shakers are used as the acoustic actuators. In order to drive the shakers, BOSS 4 channel power amplifier (1200 VI) is used . Stereo output from a MacBookAir is used to drive the power amplifier. Stereo output is split into 4 lines to drive the 4 actuators. A

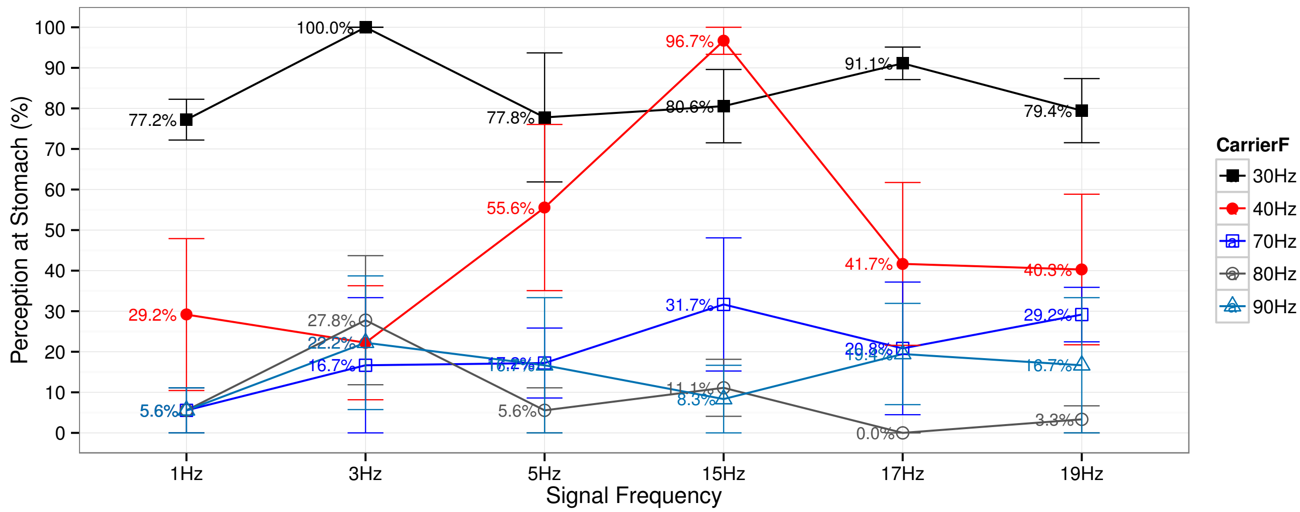


Figure 4: Haptic Perception at *Stomach*: Percentage perception with the changes of signal (f_s) and carrier (f_c) frequency

Pure-data sketch is used to drive the actuators as shown in Figure 2b.

EVALUATION

Goal of this section is to evaluate the *RippleTouch* system and its effectiveness in creating a full body haptic display. As described earlier, there are many different parameters affecting the functionality of *RippleTouch*. For an example, user demographics such as weight, built, and height, system specific variables such as damping, contact point impedance, and so on affect the performance of *RippleTouch*. However, as an initial exploration of the concept, we conducted a basic technical evaluation of *RippleTouch* system to investigate the proper frequency characteristics for amplitude modulation system to generate distinguishable haptic sensations. This includes creating a generalized synthesizer to make proper audio signals to generate full body haptic simulation and understanding the variables that affects the performance. As described before, amplitude modulation system uses two frequencies, signal frequency (f_s) and carrier frequency (f_c). A selected set of f_s and f_c pairs were used to test the *RippleTouch* system.

Participants

Total of six users (three female) participated in the experiment. All the subjects were student volunteers age ranging from 22 years to 26 years ($m = 23.6$, $\sigma = 1.3$). For control purposes, subjects were selected so that the body mass index (BMI) of the users are kept closely similar at average 20.21 ($\sigma = 1.23$).

Experiment Setup

We use three different locations; namely, head, chest and stomach. Subject's ears were covered with noise cancellation headphones and played white noise throughout the experiment to eliminate effects from sound generated by the vibrations. Six different signal frequencies (1Hz, 3Hz, 5Hz, 15Hz, 17Hz and 19Hz) with five different carrier frequencies (30Hz, 40Hz, 70Hz, 80Hz and 90Hz) were used to create 30 frequency pairs. Each frequency pair is repeated 4 iterations giving 120 total iterations per user. These 120 trials were presented in a random order. In between trials, both signal and carrier frequency will be turned off. The task of the user was to indicate the region of haptic sensation by pointing at the location (Figure 1). Initial experiments with authors indicated that head, chest and stomach to be the most likely region to feel a strong sensation. Therefore, these were selected as the dependent parameter values. Controlled input (frequency pair) along with user response (head, chest and stomach) is recorded for each trial. A user spent about 45 minutes in the experiment. For all 6 users, 720 iterations of data was recorded.

Results

Haptic Simulation on Stomach

Figure 4 shows the percentage of the haptic sensation (out of 24 total trials for a given signal (f_s) and carrier (f_c)) felt at *stomach* by the participants. Two way ANOVA showed a significant main effect of carrier frequency ($p < 0.0001$, $Df = 4$). However there was no main effect of signal frequency ($p = 0.19$) or interaction between the two ($p = 0.19$). When the carrier is $f_c = 30Hz$, perception of stimulation on stomach is significantly higher compared to other carrier frequencies ($p < 0.0001$ for all cases). In specific case of $f_c = 40Hz$ and $f_s = 15Hz$, high average perception of 96.7% (SE=3.3%) can be observed. However, this is not statistically significant compared to $f_c = 30Hz$ and $f_s = 15Hz$ with percentage 80.6% (SE=9.0%). It is apparent that low carrier frequency simulate the stomach area and users can differentiate the stimulation clearly.

Haptic Simulation on Head

Figure 5 shows the percentage of the haptic sensation (out of 24 total trials for a given signal (f_s) and carrier (f_c)) felt at *head* by the participants. Two way ANOVA showed a significant main effect of carrier frequency ($p < 0.0001$, $Df = 4$). However there was no main effect of signal frequency ($p =$

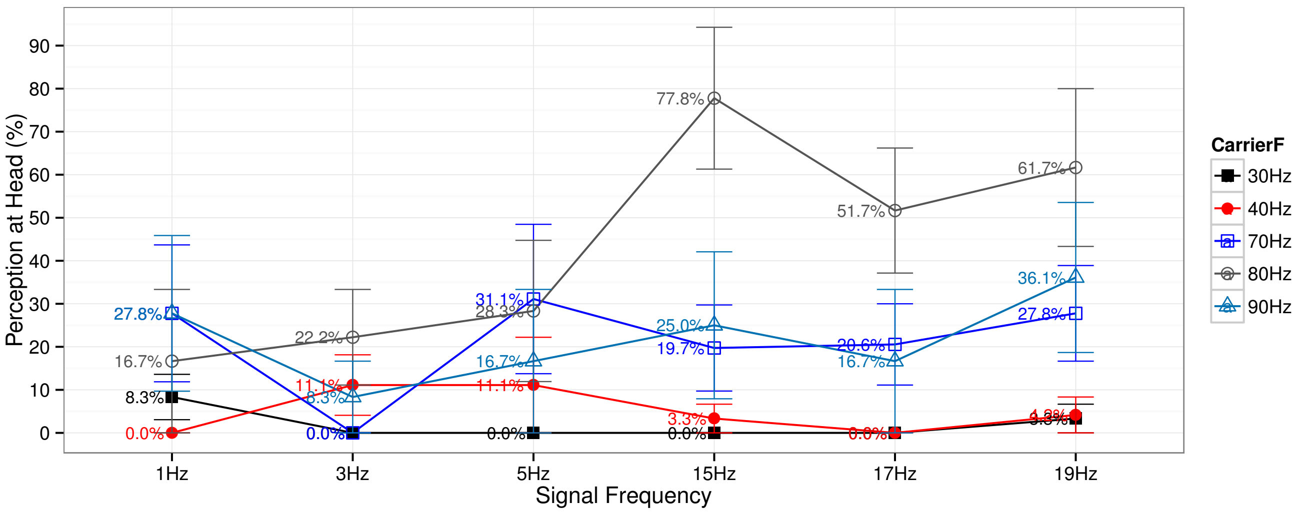


Figure 5: Haptic Perception at *Head*: Percentage perception with the changes of signal (f_s) and carrier (f_c) frequency

0.164) or interaction between the two ($p = 0.307$). At signal frequency of $15Hz$ and carrier frequency $f_c = 80Hz$, percentage perception on head (77.8%; SE=16.5%) is significantly high compared to all the other frequencies ($p < 0.05$). Therefore, $f_c = 80Hz$ and $f_s = 15Hz$ can be concluded as the most suitable frequency pair for simulating head with *RippleTouch* haptic feedback.

Haptic Simulation for Chest

Figure 6 shows the percentage of the haptic sensation (out of 24 total trials for a given signal (f_s) and carrier (f_c)) felt at *chest* by the participants. Two way ANOVA showed a significant effect of carrier frequency ($p < 0.001$, $Df = 4$), but no main effect of signal frequency ($p = 0.95$) or interaction between the two ($p = 0.96$). As shown in figure , none of the f_s, f_c pairs did not result in a haptic sensation at the chest at a high percentage. One of the possible reason for this could be haptic simulation at the chest through *RippleTouch* could be highly depend on subject demographics such as age, sex, height, weight, etc. Therefore, we conducted per subject statistical analysis on the results. ANOVA showed a significant interaction between subject and perceived location ($p < 0.001$, $Df = 10$) and significant main effect on subject ($p < 0.01$, $Df = 5$).

We found four user groups in terms of the responses to different signal frequencies. First group consists of two participants ($p4$ and $p6$). Both participants in this group showed high perception in haptic sensation at chest compared to stomach and head for given $f_c = 70Hz$ and $f_s = 1Hz$ or $3Hz$. Figure 7a shows the results of this group. Second group consist of a single user ($p2$) and Figure 7b shows the result of $p2$ to signal frequencies $f_c = 70Hz$ and $f_s = 15Hz$ or $17Hz$ or $19Hz$. It is clear from the Figure 7b that $p2$ felt consistent haptic stimulation on the chest compared to two other locations ($p < 0.01$).Third group consist of another single user ($p3$) responding to signal frequencies $f_c = 70Hz$ and $f_s = 1Hz$ or $5Hz$. $p3$ perceived consistent haptic perception on the chest (Figure 7c) compared to stomach and head. Fourth group consist of two subjects ($p1$ and $p5$ subjects) and results of these two participants show no conclusive results on haptic perception on chest at any of the tested frequency combinations.

With these results we can speculate that user demographics such as weight, height, gender, etc. may have an effect on the perception of *RippleTouch* feedback. Furthermore, there could be many other factors affecting the results other than user demographics. For example, participant's garments and posture can be some of the affecting factors. A follow-up study is needed to draw investigate these factors.

DISCUSSION

Experimental Implications

Results of the study shows conclusive evidence to demonstrate the validity of the *RippleTouch* hypothesis. Some of the carrier frequencies seems to be very effective at distinctively stimulating different areas of the body, irrespective of the signal and user demographics. This is true for $f_c = 30Hz$ or $f_c = 40Hz$. And some frequencies need the effect of the signal frequencies to fine tune the location of perception. For example, when $f_c = 80Hz$ and $f_s = 15Hz$, sensation is felt in subject's head with significantly high percentage of the time. Finally, subject's demographics played a vital role in isolating effective frequencies to create haptic sensation on the chest. Therefore, from the current experiment, we can conclude that both carrier and signal frequencies play an important role along with the user demographics in deciding the perceptual location of the haptic sensation.

Post Experimental Feedback

After the completion of all the experimental iterations by the subjects, three specific questions were asked by the experimenter regarding their experience with the *RippleTouch* system.

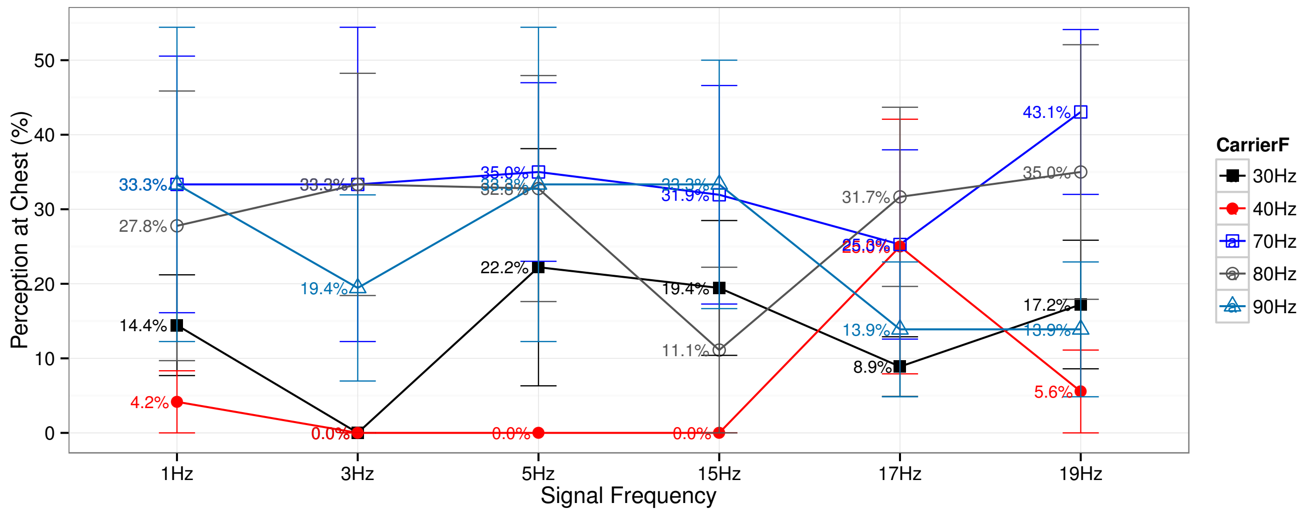
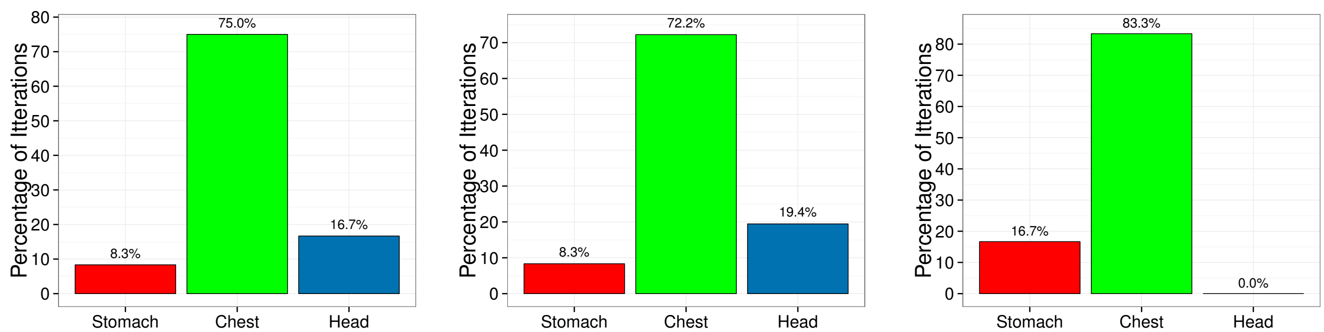


Figure 6: Haptic Perception at *Chest*: Percentage perception with the changes of signal (f_s) and carrier (f_c) frequency



(a) **(b)** **(c)**

Figure 7: Haptic Perception at: Percentage of perceived location at $f_c = 70Hz$ for a) participants $p4$ and $p6$ with $f_s = 1Hz$ and $f_s = 3Hz$, b) participant $p2$ with $f_s = 15Hz$, $f_s = 17Hz$ and $f_s = 19Hz$, c) participant $p3$ with $f_s = 1Hz$ and $f_s = 5Hz$

a) Did you feel anything uncomfortable during the test?

b) Was it fun to use?

c) In what applications would you like to have this kind of feedback?

With reference to question a), two participants indicated that the high frequency components were sometimes uncomfortable and they felt dizzy. Most of the participants suggested that the height of the *RippleTouch* chair was uncomfortable to sit for a long time. Additionally, one participant said the white noise given through the headphones were uncomfortable to listen for a long time. We do not think this is a major issue as it is not a part of the *RippleTouch* system. As shown in Figure 8, we have developed a second version of *RippleTouch* based on user feedback. This chair is significantly low in height compared to the previous setup, however, few trials with the derived frequency pairs showed this does not affect the haptic perception.

As for the question b), most users mentioned that it was surprising and exciting to feel haptic sensation in the head. Two users mentioned that they were able to feel something inside their body and it was a fun experience. For the question c), one of the most common answers was to use it with a gaming platform. Some participants mentioned the applicability of such a system in cinemas and theme parks. One user said it would be much more interesting to have a wearable form of *RippleTouch*.

Application Scenarios

There are many different types of applications which can leverage on key features of *RippleTouch* such as *Single point of contact*, *Reduced complexity* and *Easy integration*. In this section we will speculate on few important potential application domains.

Public Haptic Displays

Haptic displays are rapidly emerging in to the public media. *RippleTouch* could offer some value to this domain. Since *RippleTouch* uses a single contact point, it is ideal for public

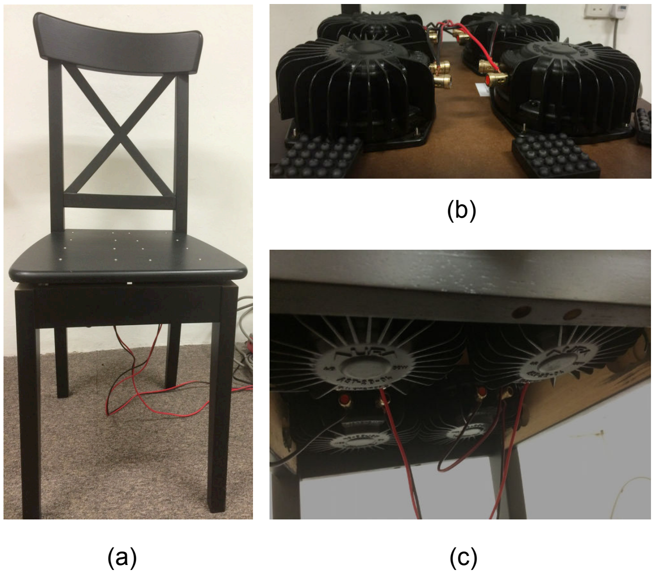


Figure 8: Enhanced prototype of *RippleTouch*: (a) chair prototype, (b) arrangement of four base range actuators underneath the chair surface and (c) Use of dampers to prevent vibration of the chair frame

setups, such as embed in a seat or a on the floor. There will not be any wearable components, making the haptic setup completely ad-hoc and interchangeable between users.

Entertainment and Communication

Integrating haptics in gaming platforms and cinemas can increase the quality of user experience. Since *RippleTouch* uses simple audio signal to actuate haptic sub-system, most of the existing audio/visual media can be easily extended to contain haptic information. For example, a video conferencing systems can use the existing audio channel to trigger the *RippleTouch* without changing the existing infrastructure. Same concept can be applied to seating in a cinema. Furthermore, existing audio components such as amplifiers and other interfaces can be used without any modification to deploy the *RippleTouch* system.

Vehicular Applications

One approach of implementing haptic interfaces in motor vehicles is to embed haptic actuator arrays in driver seat [6]. However, drivers need full flexibility to move and turn within the seat, making it is impossible to keep in contact with all the elements of such arrays. *RippleTouch* can provide a solution to this issue due to its single point of contact. *RippleTouch* can be embedded in the bottom of the seat, where driver will be in constant contact and still utilize the resonant principle to stimulate different parts of the driver's body.

Limitations

RippleTouch is an extremely low resolution haptic display to convey subtle and affective feedback. It is not design to deliver complex information. With the current version of the prototype, we managed to simulate haptic sensation in three locations in human body without direct contact. We believe *RippleTouch* concept can be extended to increase the resolution by further improving on the synthesis algorithm and integrating all the variables that affect the simulation such as user demographics.

In its current status, *RippleTouch* only support changing the sensation point along the vertical axis of the human body. For example, it is not possible to create a haptic simulation that goes from left to right or front to back with the current version. However, in a properly controlled setup, *RippleTouch* actuators should be able to operate as an *phased array* to achieve directivity in stimulation.

As any other haptic device, *RippleTouch* generate some audible noise and this can be an undesirable byproduct.

Future Work

Further Evaluation

We are planning to evaluate the effect of user aspects such as height, weight, gender on the *RippleTouch* system. Furthermore, we are planning to explore the effect of other wave properties such as phase changes, intensity as independent variables and possibilities of exploring wave concepts such as standing waves.

Application Development

RippleTouch currently does not have functioning applications. We are planning to develop a few proof of concept applications including a computer game, a video communication system with *RippleTouch* feedback.

Extending RippleTouch *Concept*

In the current prototype, *RippleTouch* is designed to simulate individual locations on the human body. However, there are alternative ways to integrate other perceptual phenomena such as *phantom sensation* and *apparent motion* to create a continuous flow of haptic sensation on the body [14, 1, 10]. Furthermore, concept can be further explored manipulating other parameters of waves, such as amplitude and the phase. Possibly, this can lead to changing the stimulus location, intensity and the type. We are planning to explore these possibilities with *RippleTouch* in the future.

CONCLUSION

In this paper we presented *RippleTouch*, a low resolution haptic interface that is capable of providing haptic stimulation to multiple areas of the body via a single point of contact. The system was evaluated to investigate the effects of frequency characteristics of amplitude modulation system used. The results demonstrate that we can effectively create haptic sensations at different parts of the body with a single contact point. Our results are conclusive that at least three areas of the body can be distinctively simulated using an actuator system embedded in a chair. We believe *RippleTouch* concept would open new possibilities in multi-modal interfaces for human computer interaction.

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