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# Surface Waves and Spatial Localization in Vibrotactile Displays

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## ABSTRACT

The locus of vibrotactile stimulation is often used as an encoding cue in tactile displays developed for spatial orientation and navigation. However, the ability to localize the site of stimulation varies as a function of the number and configuration of the vibrating motors (tactors) in the display. As the inter-tactor distance decreases it has been found that the ability to localize a point of stimulation diminishes. One factor that may limit tactile localization is the surface wave elicited by vibration that propagates across the skin at a velocity that depends on the frequency of vibration and the viscoelastic properties of the skin. A material that simulates the stress-strain characteristics of human skin was used to measure the characteristics of surface waves during vibrotactile stimulation. Accelerometers glued to the simulated skin at fixed distances from the activated tactors were used to measure the amplitude of the acceleration as a function of distance as well as the propagation velocity. It was determined that at a distance of 60 mm from the site of activation, the surface wave was on average attenuated to less than  $1 \text{ m/s}^2$ . This suggests that for this type of tactor an inter-tactor distance of at least 60 mm would be optimal for a display in which the locus of stimulation is used as an encoding variable. It seems that much of the difficulty encountered in identifying the locus of a vibrotactile stimulus in multi-tactor displays may result from small inter-tactor distances.

**CR Categories:** G.3 [Mathematics of Computing]: Probability and Statistics – Experimental Design; H1.2 [Model and Principles]: User/Machine System; H.5.2 [Information Interfaces and Presentation]: User Interfaces – Theory and methods; User-centered design

**Keywords:** tactile display, touch, torso, localization, tactors

## 1. INTRODUCTION

Body-based vibrotactile displays have been developed for a number of applications ranging from sensory substitution systems for the visually or hearing impaired [1] to assisting with navigation and spatial orientation in unfamiliar environments [2-4]. In the latter case, the spatial coordinates of a tactile stimulus delivered to the skin are used to identify the location of an event in the external world or to indicate the direction of navigation. It seems to be very intuitive to infer an external direction normal to the plane of the skin from a single point of stimulation on the skin surface [5]. The locus of cutaneous stimulation has therefore been used in tactile displays to convey information about the external world or to direct visual attention [6].

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One of the advantages of using the location of a tactor as an encoding cue is that anatomical landmarks can facilitate identifying the site of the tactile input (e.g. on the elbow, near the wrist) and so the number of sites available is potentially quite large. However, most tactile displays used for spatial cuing have been mounted on small defined areas of the body such as the dorsal surface of the forearm or the lower back. At these locations the ability to localize a point of stimulation in a multi-tactor display depends on the inter-tactor distance and number of tactors in the display [7-9]. In general, these two variables are coupled in that as the number of tactors increases, inter-tactor distance decreases. For a one-dimensional display mounted around the waist, Cholewiak et al. [10] found that as the number of tactors increased from six (inter-tactor spacing of 140 mm) to twelve (inter-tactor spacing of 72 mm) localization accuracy decreased from 97% to 74% correct, with most of the decrement in performance occurring when the number of tactors was greater than eight.

With two-dimensional tactile displays, the ability to localize a point of vibrotactile stimulation is very dependent on inter-tactor spacing. Using a 3-by-3 tactor array on the back with an inter-tactor spacing of 60 mm, Lindeman and Yanagida [11] found that participants were able to identify the location of a single vibrotactile stimulus on 84% of the trials. In contrast, Jones and Ray [9] reported that with their 4-by-4 tactor array on the back which had an inter-tactor spacing of 60 mm in the horizontal direction and 40 mm in the vertical direction, participants identified the location of a vibrotactile stimulus on only 59% of the trials. However, most errors involved mislocalization by a single tactor, and so when the responses were coded in terms of localizing stimulation to within one tactor of the one activated, the overall response rate was 95% correct. In this experiment, participants were more accurate in identifying the correct column of tactor activation (87% correct) than the row (68% correct), which presumably reflected the smaller difference in inter-tactor spacing in the vertical as compared to the horizontal direction. It appears that the increase in the number of tactors in the display and the smaller inter-tactor spacing both contributed to the decline in performance when compared to that of Lindeman and Yanagida [11]. Similar results have emerged from localization studies on the forearm, in which the width of the forearm limits the dimensions of the display. When a 3-by-3 array with an inter-tactor spacing of 25 mm was tested on the dorsal surface of the forearm, participants were able to identify the location of the vibrotactile stimulus on only 50% [7] and 53% of the trials [12]. In the two latter studies, localization performance was slightly better for columns than for rows on the forearm.

The results from a number of studies examining tactile spatial localization on different areas of the body are summarized in Table 1. These data indicate that over the range of frequencies used (80-250 Hz) vibrotactile frequency has little effect on the

ability to localize a point of stimulation. It is also important to note that vibrotactile sensitivity is not related to the ability to localize a point of stimulation. Vibrotactile thresholds can be quite uniform across a skin surface showing marked variation in vibrotactile localization [8]. Inter-tactor distance and the number of factors in the display appear to exert the most influence on localization and must be considered carefully in the design of a tactile display used to communicate spatial information.

Table 1. Localization accuracy at different sites

Site	Array size	Frequency	Tactor spacing	Localization accuracy
Wrist (volar and dorsal)	3 by 3	150 Hz	25 mm	50% <sup>7</sup>
Forearm (volar and dorsal)	3 by 3	90-110 Hz	25 mm	53% <sup>12</sup>
Forearm (volar)	7 by 1	100/250 Hz	25 mm	55% <sup>8</sup>
Waist	8 by 1	100 Hz	80-100 mm	98% <sup>9</sup>
Waist	12 by 1	250 Hz	72 mm	74% <sup>10</sup>
Back	3 by 3	91 Hz	60 mm	84% <sup>11</sup>
Back	4 by 4	100 Hz	40 mm (V) 60 mm (H)	59% <sup>9</sup>
Abdomen	4 by 6	80/250 Hz	50 mm	51% <sup>13</sup>
Torso (semicircle)	7 by 1	250 Hz	60 mm	77% <sup>10</sup>

A metric that is often used to characterize the performance of tactile communication systems is information transfer (IT) which measures the increase in information about a signal transmitted that results from knowledge of the received signal [14, 15]. The IT associated with the various tactile displays described in Table 1 ranges from 1.24 [7] to 2.78 bits [13], which is considerably smaller than the bits of information potentially available (i.e. 4.9 bits for a 24-tactor array).

One factor that probably influences the ability to localize precisely a vibrotactile stimulus is the surface wave on the skin created by activation of the tactor. Skin is a viscoelastic material that absorbs some of the energy imposed on it during vibration and transmits some energy in the form of a surface wave. The transmitted energy travels in a wave and the shearing forces produced diminish at a rate proportional to the inverse square of the distance from the source. The velocity of the surface waves created by vibrotactile stimulation has been estimated to range from 2 to 40 m/s based on stroboscopic illumination [16]. The exact velocity depends on several variables including the frequency of vibration, skin temperature and the constituency of the underlying tissue [17]. Even though the intensity of these waves diminishes with distance, vibrations applied to the finger can be seen traveling up the arm many centimeters from their source [8]. This means that surface waves may excite afferent units located some distance from the site of skin stimulation, possibly contributing to errors in tactile localization. Attempts to reduce this effect have involved placing a rigid surround around the moving contactor (e.g. C2 tactor) to dampen the traveling waves. Vibrotactile thresholds can increase or decrease when the surround is added, depending on the underlying receptor systems and the size of the contactor stimulating the skin [18]. Because surface waves may contribute to errors in localization and in perceiving tactile patterns [6], characterizing their properties is important to the design of tactile displays.

Previous research with a silicone-rubber simulated skin (Skinsim) has demonstrated that it provides a useful substrate for

testing the responses of skin to different vibrotactile inputs and configurations of a multi-tactor display [19]. The objective of the present set of experiments was to characterize the properties of traveling waves evoked by vibrotactile stimulation initially in the simulated skin so that the optimal spacing of factors in a display used for localization could be estimated.

## 2. EXPERIMENT

The experiments used simulated skin in preference to human skin so that the factors and accelerometers could be attached very firmly to the skin with epoxy and repeated measurements could be taken under different conditions with the accelerometers in precisely specified positions.

### 2.1 Apparatus

The factors used in the experiment were pancake motors (Sanko Electric, Model 1E120) that vibrate when a DC voltage is applied to the motor causing an eccentric mass to rotate around the center of the motor. The axis of rotation of the motor is perpendicular to the skin surface. These motors have been used in a number of tactile displays [6,11,12]. The frequency of vibration is directly proportional to the motor's speed which is a function of the driving voltage. At 3 V, they are rated to oscillate at a rate of at least 4500 rpm (75 Hz), with a current of 45 mA. The motors are encased in plastic (Smooth-On, Inc) to make them more robust and to increase the contact area between the skin and tactor. The encased factors have a surface area of approximately 300 mm<sup>2</sup> and a mass of 3.3 g. When activated at 3 V, the peak force generated in the plane of rotation of the eccentric mass is approximately 0.7 N [19], with a resulting peak pressure on the skin of approximately 2.3 kPa.

Three encased factors were glued to the Skinsim (a two-part silicone rubber compound: Smooth-On, Ecoflex 00-30 with a silicone fluid (Smooth-On, Silicone Thinner), and a one-axis accelerometer (Measurement Specialties ACH-01) was glued to the top of each tactor and placed at 20 mm intervals from the factors, as shown in Figure 1. The accelerometers have a sensitivity range of 7-11 mV/g and a noise level of about 0.2 m/s<sup>2</sup>. They can record accelerations ranging from 2 Hz to 20 kHz, up to 1470 m/s<sup>2</sup>. They have a mass of 3.03 g, which means that the mass of the factors is almost doubled when the accelerometers are attached. The effect of added load on the peak frequency and mean acceleration of tactor activation was determined in a separate series of experiments.



Figure 1. Tactors (white) mounted on the viscoelastic substrate (Skinsim) with accelerometers (black) mounted on the factors and Skinsim to measure movement when the factors are activated.

### 2.2 Procedure

Each tactor was activated at 3.3 V (Agilent power supply, Model E3631A) for 10 s and then turned off for 10 s. The last 5 s of data during tactor activation were analyzed. The sequence of activation was repeated 10 times for each tactor. Data were recorded from the amplifiers (Measurement Specialties, ACH-01) at 10 kHz using a data acquisition board (NI-DAQ). The pure delay in the traveling wave was used to estimate its velocity.

In order to determine the effect of mass loading on the response of the factors, various masses ranging from 2 to 50 g were attached to the top of the factor using double-stick foam mounting tape. In the “no-load condition” the factor still had the accelerometer and cable attached to it, so that its acceleration could be measured.

The linearity of the Skinsim was determined by measuring the superposition of two traveling waves. Two factors spaced 80 mm apart were activated and an accelerometer was positioned midway between them. The predicted superposition, assuming linearity, was compared with the measured acceleration midway between the factors.

In order to verify that the simulated skin was comparable to human skin, five factors with accelerometers mounted on them were glued (Liquid bandage™) along the ventral forearm of three subjects and measurements made of the peak frequency of vibration.

### 2.3 Results

Activation of a factor created a surface wave in the Skinsim that decreased in amplitude with distance as illustrated in Figure 2. At a distance of 60 mm, the surface wave was attenuated to less than 10% of its initial acceleration, and at this distance the acceleration was less than  $1 \text{ m/s}^2$ . For this type of vibrating motor, an inter-factor distance of 60 mm would seem optimal for a display in which the locus of stimulation is used as an encoding variable. At smaller inter-factor distances, the amplitude of the surface wave is such that it could be interpreted as indicating that a factor at a different location has been activated. The recommendation of an inter-factor distance of 60 mm needs to be validated in human localization studies, but seems an appropriate benchmark based on the data presented in Table 1. In hairy skin, the vibrotactile threshold at 70 Hz is around  $2 \mu\text{m}$  [20]; in the present experiment the displacement of the skin at a distance of 40 mm from the activated factor was approximately  $17 \mu\text{m}$ . In the context of tactile localization, however, observers must encode the site of stimulation in addition to its amplitude.

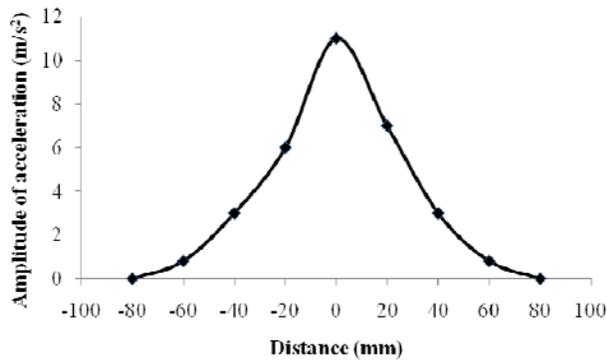


Figure 2. Average amplitude of acceleration at various distances from the factors. The zero point represents the location of the factor activated.

The general equation for a traveling wave with no damping is given by:

$$a = a_0 \sin \left( \frac{2\pi}{\lambda} (x - ct) \right)$$

where  $a_0$  is the amplitude of the acceleration,  $\lambda$  is the distance between adjacent points that are in phase (i.e. wavelength,  $\lambda=c/f$ ), and  $c$  is the speed of the waveform [21]. The propagation velocity was determined using nonlinear least squares estimation from the

phase shift of the waves measured at the locations at which the accelerometers were positioned. The acceleration measured on the vibrating factor was noisy and so was digitally low-pass filtered using a fifth-order non-causal Butterworth filter with a cut-off frequency 20 Hz higher than the peak of the wave. As the Skinsim acted as a low-pass filter, the measurements from the other accelerometers did not need to be filtered.

The time taken for the traveling wave to reach each of four accelerometers placed at various distances from the activated factor is illustrated in Figure 3. The speeds of the surface waves on the skin will probably vary with the frequency of the factor, which for pancake motors has been shown to range from 90-160 Hz [19].

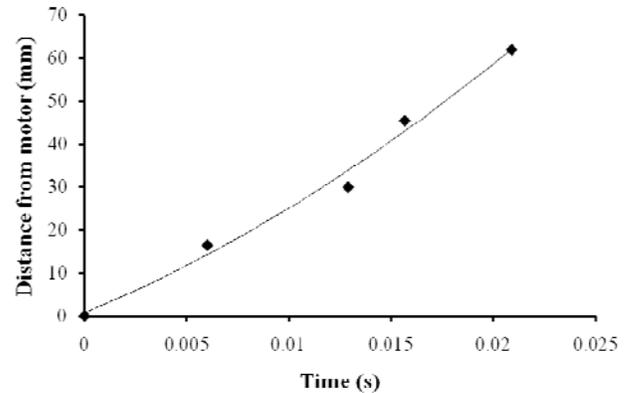


Figure 3. Distance from the factor as a function of time taken for the waveform to reach that distance.

The effect of adding mass to the factor was evaluated in order to determine how much the peak frequency and acceleration of the factor changes as a function of added load. The peak frequency and mean acceleration decreased with loading, but a mass of 50 g was required to reduce the peak frequency by 7 Hz. The mean acceleration changed by  $1 \text{ m/s}^2$  when the load increased from 0 (i.e. 3.3 g with the accelerometer on the factor) to 3 g.

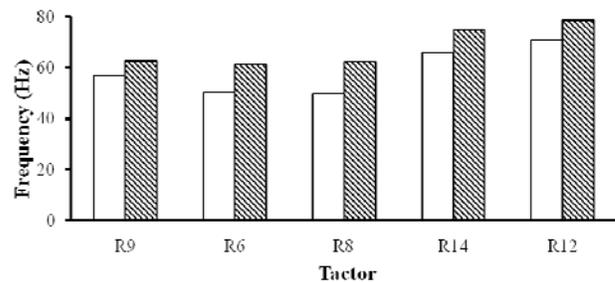


Figure 4. Peak frequency of vibration of five factors measured on Skinsim (white bars) and the skin on the forearm (hatched bars).

A comparison between the peak frequency of factor vibration on Skinsim and the human forearm (see Figure 4) indicated that the frequencies are comparable on the two surfaces, although the peak frequency is on average 13% higher on the forearm. Skinsim was developed to have similar stress-strain characteristics to pig skin [19]. The difference in peak frequency measured in the present experiment presumably reflects the properties of the underlying tissue and suggests that the propagation velocity of a surface wave would also be slightly higher on skin.

### 3. CONCLUSIONS

The results from this experiment indicate that surface waves produced by vibrotactile stimulation of the skin travel over considerable distances when considered in terms of the spatial configuration of tactile displays. For this type of factor, the amplitude of vibration is such that it could often be mislocalized as arising from a source up to 40 mm from its origin (see Figure 2). It would appear therefore that much of the difficulty encountered in identifying the locus of a vibrotactile stimulus in a multi-tactor array (see Table 1) results from small inter-tactor distances. On the basis of the present results and studies that have examined tactile localization with two-dimensional tactile displays [9,13], it would appear that if spatial cues are to be presented on large sensory surfaces such as the back or abdomen, inter-tactor distance should be maximized if precise spatial mapping is required, such as between a tactile and visual target [22].

The experiments described in this paper provide the basis for developing an experimental system that can be used to perform comparable experiments at different sites on the human body. A new experimental system is being developed in our laboratory involving a custom-designed pair of low-mass Lorentz force actuators that incorporate precision displacement sensors. One of the actuators is used to perturb the skin at a point and at an adjustable but fixed distance from the first, the second actuator is used to sense the resulting skin displacement. Tailored stochastic skin displacements applied using the first actuator are detected by the second actuator and nonlinear system identification techniques are used to measure the skin mechanical propagation velocities [23]. The advantage of this new experimental system is that phase differences caused by the pure delays associated with propagation velocity can be distinguished from the viscoelastic mechanical dynamics of skin.

Mechanical studies of the skin are essential to the effective design of tactile displays as they contribute to our understanding of how the skin responds to different stimuli. As new actuators for tactile displays are developed in which a greater range of variables can be controlled, it will be essential to characterize both the mechanical and perceptual responses of the human user to these devices.

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