

# Electrostatic Modulated Friction as Tactile Feedback: Intensity Perception

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**Abstract.** We describe the preliminary results from an experiment investigating the perceived intensity of modulated friction created by electrostatic force, or electrovibration. A prototype experimental system was created to evaluate user perception of sinusoidal electrovibration stimuli on a flat surface emulating a touch screen interface. We introduce a fixed 6-point Effect Strength Subjective Index (ESSI) as a measure of generic sensation intensity, and compare it with an open magnitude scale. The results of the experiment indicate that there are significant correlations between intensity perception and signal amplitude, and the highest sensitivity was found at a frequency of 80 Hz. The subjective results show that the users perceived the electrovibration stimuli as pleasant and a useful means of feedback for touchscreens.

**Keywords:** electrovibration, tactile, intensity, perception.

## 1 Introduction

Touch provides a rich channel through which to communicate and has been the focus of much research [1] [2] [3] [4] [5]. There are several different sub-modalities within touch. Tactile feedback (commonly vibrotactile mechanical stimulation of the skin) is the best understood and most used in HCI. Electro vibration is part of the same sensory system but has been relatively underutilized in interactive systems due to the lack of available hardware. However, recent advancements in touchscreen electrovibration technology mean that mainstream usage is now becoming possible. Electro vibration is created using electrostatic friction between a surface and a user's skin [5]. Passing an electrical charge into the insulated electrode creates a small attractive force when a user's skin comes into contact with it. By modulating this attractive force a variety of sensations can be generated [6].

The properties of electrovibration are quite different to those of standard vibrotactile feedback. In order to use electrovibration feedback effectively in user interfaces, it is important to identify the available design parameters. Tacton and Haptic Icon

[7] [8] designers use parameters such as intensity, waveform, rhythm and spatial locations, but the electrovibration domain has not been investigated with such an approach as yet. Given the importance of intensity as a parameter in vibrotactile and other haptic research [8], this paper investigates the perceived intensity levels of electrovibration feedback and identifies the most distinguishable levels of intensity.

We report the results of a psychophysical experiment and subjective evaluation of electrovibration intensity with a focus on amplitude and frequency manipulations, and the effects of gender and handedness on perception. The results of this research will aid designers in the creation of electrovibration feedback for touchscreen interaction with perceptually discriminable intensity levels.

## 2 Related Work

### 2.1 The History of Electro vibration

In 1950, Mallinckrodt [9] identified that electric flow in brass light sockets generates a different feeling when a current is flowing. Later, through experiments conducted on this phenomenon, he observed that such sensations were created through induced electricity.

Electrocutaneous stimulation has also been studied as a psychophysical phenomenon. But in electrocutaneous stimulation, a real electric current is passed through the body as a nerve-stimulating agent. In Higashiyama's work [6] they discuss the various combinations of electrode placements to create pleasant feedback (the authors defined the term "pleasant feedback" as a less painful or less uncomfortable feeling).

Following on from this, a micro fabricated electrostatic display was tested by Tang *et al.* [10]. An electrode array with different resolutions was created where each electrode could be controlled separately. The study showed that more than 7.6 mm distance is needed to feel each electrode separately. The same concept was used by Fukushima *et al.* in their "Palm Touch Panel" [11] [12]. The Panel stimulated the palm of a hand using electrodes with controlled electric shocks instead of electrovibration.

The main focus of electrovibration research is in the usage of haptic feedback for telepresentation interfaces [1] and for visually impaired people, with studies targeted towards finding the thresholds in sensation using different materials [13] [14].

### 2.2 Current Electro vibration Systems

Parallel to academic research of galvanic electrotactile stimulation, and dedicated isolated electrode arrays for electrovibration, Senseg<sup>1</sup> started creating a commercially applicable system solution for utilizing electrovibration in 2007. With advancements in grounding arrangements, display material and structure, and stimulus signal characteristics, Senseg was able to bypass lot of the challenges mentioned by [1, 11, 14, 15]. The key emphasis has been in integrating electrovibration feedback with mobile

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<sup>1</sup> <http://www.senseg.com>

devices using active surfaces called *tixels*, the tactile pixel [15]. The experiment reported here makes use of Senseg's tixel.

In 2009, Disney Research announced "Tesla Touch", which uses similar kind of mechanism to produce haptic feedback. The key difference is that Tesla Touch implemented on an experimental desktop-based multi-touch system while the Senseg implementation works on mobile and handheld devices. Bau *et al.* [5] have studied the noticeable differences in frequency and amplitude changes in different frequencies. 80Hz, 120Hz, 180Hz are reported to have more than 25% of Just Noticeable Difference (JND) and for 270Hz and 400Hz, the JND is less than 15%.

Amberg *et al.* [4] have presented a tactile input device called STIMTAC which works by changing the friction similar to Senseg and TeslaTouch. But the only difference is that it reduces the friction by creating an air bearing between the finger and surface in addition to the friction. STIMTAC adopted the friction reduction technique from T-PaD designed by Winfield *et al.*, and later introduced a larger area version of T-PaD (LATPaD) in 2010 [16] [17]. One of the main drawbacks of those systems is the lack of transparency; therefore it is not possible to integrate it into any current touchscreen displays. But in 2011 Levesque *et al.* [2] presented a group of frictional widgets using the same mechanism. There they used a transparent surface on top of a graphic display. Although the implementation focuses on reducing the friction, they concluded that programmable friction could increase the awareness of the system and improve the appreciation of an interface.

Although there are several existing implementations of electrovibration for touchscreen interaction, there have been very few studies into user perception of electrovibration stimuli. In studies with vibrotactile stimulation using Eccentric Vibration Motors (ERM) and Linear Resonator Actuators (LRA), it has been shown that 250Hz is the optimum frequency where people feel the vibration with a very low level of displacement [18]. The research described here attempts to analyse electrovibration feedback in a similar manner to establish the optimum frequency and amplitude levels that can be used to design electrovibration feedback with different intensity levels for touchscreen interaction.

### 2.3 Electrovibration Intensity

The perceived intensity of electrovibration depends on many factors. The basic principle behind electrovibration is the attractive electric Coulomb force between the isolated electrode and the touching finger [9]. It can be conveniently expressed as Maxwell pressure:

$$P = \frac{1}{2} \varepsilon E^2 \quad (1)$$

Where  $\varepsilon$  is dielectric constant,  $E$  is electric field  $E = V/d$ ,  $V$  = voltage difference between electrode and conductive tissue in finger,  $d$  = effective distance between charges. Distance is comprised of the electrical insulator thickness, and (effective) finger skin thickness. The basic mechanism for electrovibration is thus quadratic with

respect to the stimulus voltage. One consequence of this quadratic behavior is that it doubles the frequency of sinusoidal drive signals.

When the attraction force is modulated with a stimulus signal, it vibrates the finger skin and can be felt as a normal vibration. For a finger sliding on the tixel surface, the normal vibration is coupled with the lateral force of kinetic friction between the skin and surface. The resulting modulation of friction force creates a large lateral vibration of the skin. The factors that affect the modulated friction include the friction coefficient (nonlinear) and finger biomechanics, modulation signal shape, and the user's potential grounding (effective voltage).

These factors are carefully taken into account in the experimental setup design. We used a plastic film that has relatively stable friction properties, and has an even thickness profile.

### 3 Experiment: Evaluating Perceived Intensity

The aim of this experiment was to investigate what levels of frequency and amplitude in electrovibration increase the perceived intensity of the stimuli. This was studied with a magnitude estimation approach, and using a given index scale, ESSI (outlined below). A qualitative survey was also performed to assess the participants' overall perception of the stimuli.

#### 3.1 Magnitude Estimation

Psychophysical scaling has a history as long as psychophysics. In 1850, Fechner came up with the concept of arithmetical representation of sensations [19]. Each psychophysical scaling task can be categorized in to one of the following:

- (a) Subjects rate the sensation in an ordinal scale;
- (b) Subjects adjust the stimuli to create equal sensory intervals;
- (c) Subjects assign a number to represent the magnitude of the sensation (Magnitude Estimation).

In 1988, Gescheider [19] pointed out that magnitude estimation is the most used scaling mechanism in psychophysical evaluations. According to this method, the user starts rating the sensation by giving an arbitrary value at the starting point of the test. But later the user builds up his/her own scale around the given previous ratings.

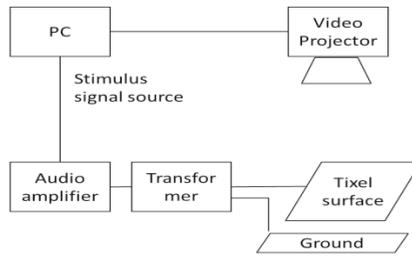
#### 3.2 ESSI Rating Scale

Alongside the magnitude estimations, we propose a practical perception strength index scale, Effect Strength Subjective Index (ESSI) for evaluating electrovibration perception. The design of the ESSI rating is based on previous studies with vibration alert perception, where a 4-value strength scale was used [20]. This numerical index makes use of Likert scales, which are widely applied in psychophysics, and in acoustic and visual research [21].

The ESSI scale is a 6-value discrete scale where 0 represents the non-perceived signals and 5 represents signals that are considered to be ‘too strong’. The value 3 was defined as “Medium” and it is considered to be the optimum value for stimuli.

### 3.3 Test Hardware

The test system uses a PC as the signal source, an audio amplifier and transformer, and the tixel test surface with conductive and insulating layers. The insulating layer was made from a screen protector film (iPad Screen protector with a thickness of 125  $\mu\text{m}$ ). Around the test surface, a ground reference surface was arranged (electrostatic matt) that the user could touch with their non-dominant hand. This provided a stable grounding of the user potential, leaving the drive voltage between the dominant hand and the test surface. The drive signal was floating, and there was a 5 Mohm serial resistor in series with the output. The system was capable of driving voltages up to 2.4 kV peak to peak in the frequency range of 40 to 600 Hz. The system schematics are shown in Figure 1.



**Fig. 1.** Test system hardware. The user slides their finger on the tixel surface, where the visual gesture hint is projected. The non-dominant hand is placed on the ground surface.

### 3.4 Stimuli

All the stimuli used in the experiment were pure sine waves. There were 13 different signal patterns used in this test. In the original pilot studies we conducted to identify the frequency scale, we tested 40Hz-200Hz with 40Hz intervals. In that study we found that 80Hz was the most sensitive vibration level and using a maximum of 200Hz did not cover a large enough scale. Hence we increased the range to 320Hz. In the pilot study, the intensity ratings of 120Hz stimuli were not significantly high despite that fact that 125Hz should be the most sensitive level of vibration for the skin. Therefore, in the study reported here, we examined a range of frequencies using the following scale: 40Hz, 80Hz, 160Hz, 240Hz and 320Hz. 0dB, -6dB and -12dB were used as amplitudes. -6dB and -12dB were selected since they resemble the signals closer to the half and the quarter of the original signal. 0dB corresponds to a 1.2 kV peak. All combinations of frequency and amplitude were used in the test except 240Hz/-12dB and 320Hz/-12dB. These stimuli were excluded from the experiment after pilot studies revealed them to be unperceivable.

### 3.5 Subjects

We recruited 26 volunteer participants (mean age: 25,5; s.d.: 4,4), mostly students or members of the University of Helsinki, who gave their informed consent to participate in the study and received two movie tickets as compensation. There were an equal number of males and females, left-handed and right-handed participants. Handedness was determined by the Edinburgh Handedness Inventory [22], which showed that three participants were actually ambidextrous, even though they were not aware of it.

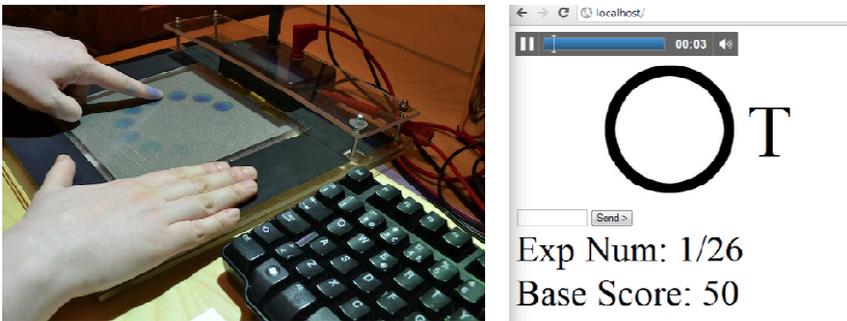
### 3.6 Methodology

Before the actual test began, all participants took part in short tutorial at the beginning of the session to acquaint themselves with the Tixel hardware and electrovibration feedback. The participants' task was to make a continuous circle gesture with the index finger of their dominant hand, tracing an image projected from above onto the test bed (see Figure 2). We instructed participants to keep the other hand on the grounding surface while doing the gesture.

There were two phases in the experiment: magnitude estimation and ESSI ratings. Firstly, a magnitude estimation method was used where participants assigned an arbitrary number of their own choice to the intensity of a baseline stimulus presented. Participants were then presented with a series of further stimuli and asked to assign an intensity number reflecting its perceived intensity relative to the baseline. Overall there were 26 tasks in the experiment using a random baseline stimulus (chosen from the 13 frequency/amplitude combinations). For example, a participant could be presented with the 80Hz 0dB stimulus as the baseline and asked to assign a weight value to the 40Hz -12dB stimulus in comparison to the baseline (see Fig. 2b).

The second phase of the experiment focused on ESSI ratings. Users felt the stimuli in a random order, and rated them one by one using the ESSI scale.

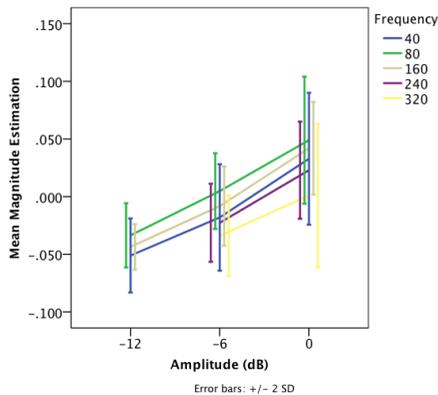
Before the test there was a short questionnaire, and it was repeated after the test with additional qualitative questions of user perceptions. The experiment took approximately 30 minutes to complete. Due to the repetitiveness of the task, participants could interrupt their performance at any time, and the subjects lifted their index finger from the system between each task.



**Fig. 2.** (a) left: Test setup (b) right: Magnitude Estimation Test

### 3.7 Magnitude Estimation Results

Figure 3 shows the average magnitude estimation for each amplitude and frequency combination. Given that participants could assign any intensity baseline rating they wished, all data were normalized prior to analysis. A partial correlation (taking frequency into account) showed a significant correlation of 0.79 ( $p = 0.01$ ) between amplitude and perceived intensity. This correlation suggests that higher amplitude levels results in the perception of increasing intensity. Although there is no significant correlation between frequency and perceived intensity, the graph indicates that 80Hz stimuli are rated higher than all other frequencies.



**Fig. 3.** The mean magnitude estimation for each amplitude level grouped by frequency showing a positive correlation between intensity and amplitude

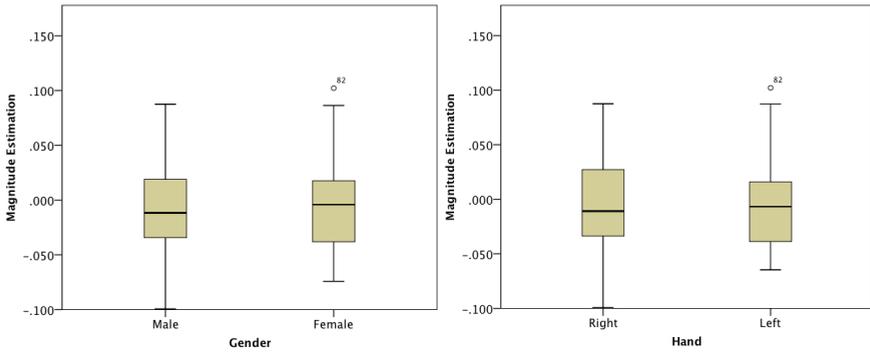
Analysis of the intensity estimates using a MANOVA showed a significant main effect for amplitude ( $F=367.2$ ,  $df = 2$ ,  $p = 0.001$ ) and also for frequency ( $F = 35$ ,  $df = 4$ ,  $p = 0.001$ ). There was no significant interaction between the two factors. *Post hoc* Tukey's HSD tests showed many significant differences. The most notable results being stimuli using 80Hz and 0dB or 160Hz and 0dB are perceived to be significantly more intense than all other stimuli.

### Gender

The participants were evenly balanced in terms of gender. The average intensity estimations for each gender are shown in Figure 4(a). An ANOVA showed no significant differences in the magnitude estimations for gender type ( $F = 0.004$ ,  $df = 1$ ,  $p = .949$ ).

### Handedness

Half of the participants (13) stated that they were right-handed while the other half considered themselves to be left-handed. The average intensity estimations for each hand are shown in figure 4(b). An ANOVA showed no significant differences in intensity estimations for each hand ( $F = .832$ ,  $df = 1$ ,  $p = .362$ ).

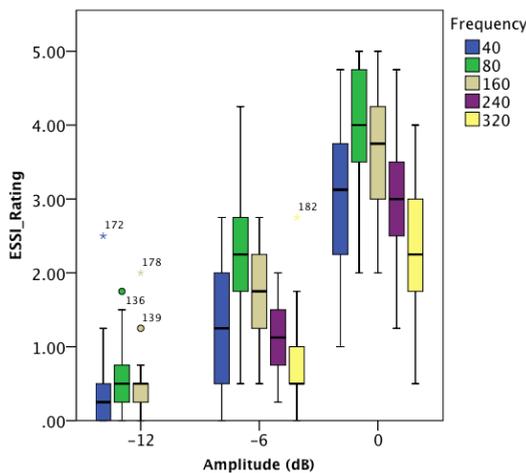


**Fig. 4.** (a) left: Average Intensity Estimations by Gender; (b) right: Average Intensity Estimations by Dominant Hand

### ESSI Results

Figure 5 shows the average ESSI rating for each amplitude/frequency combination. A partial correlation (taking frequency into account) showed a significant correlation of 0.801 ( $p = 0.01$ ) between amplitude and ESSI rating. This correlation suggests that higher amplitude levels results in the perception of increasing intensity. Although there is no significant correlation between frequency and ESSI, the graph indicates that 80Hz stimuli are rated higher than all other frequencies. This corresponds with the magnitude estimation results.

Analysis of the intensity estimates for each stimulus using a MANOVA showed a significant main effect for amplitude ( $F=388$ ,  $df = 2$ ,  $p = 0.000$ ) and also for frequency ( $F = 30.8$ ,  $df = 4$ ,  $p = 0.000$ ). There was no significant interaction between the two factors. *Post hoc* Tukey tests show similar results to those shown in Table 1. Once again, stimuli using 80Hz and 0dB were perceived to be significantly more intense than all other stimuli except 160Hz and 0dB.



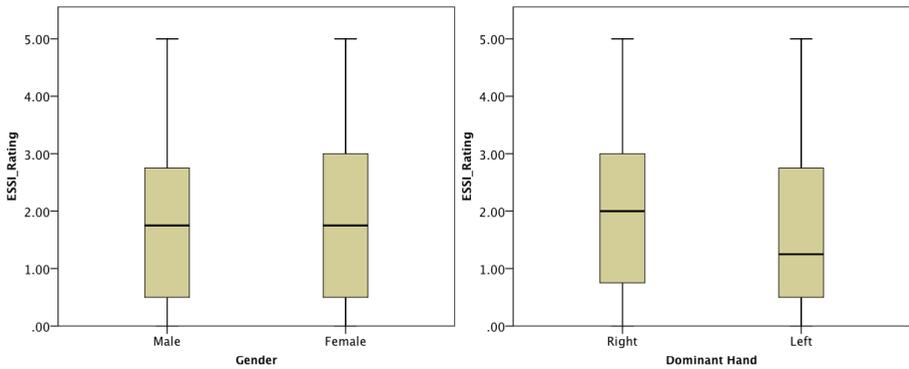
**Fig. 5.** Average ESSI ratings (max 5)

## Gender

Once again, an ANOVA showed no significant difference between ESSI ratings and gender as shown in Figure 6a ( $F=0.001$ ,  $df = 1$ ,  $p=.977$ ).

## Handedness

An ANOVA showed a significant difference in ESSI ratings for left and right handed users ( $F=4.5$ ,  $df = 1$ ,  $p=0.033$ ). The results indicate that right-handed users rate the stimuli as 18% more intense than left-handed users (Figure 6b).



**Fig. 6.** (a) left: Average ESSI Rating by Gender. (b) right: Average ESSI Rating by Dominant Hand

## Questionnaires

The post-study questionnaire explored the participants' general reaction to the system and stimuli. There were 8 statements using a 5-point Likert scale, where 1 corresponded to "strongly disagree" and 5 corresponded to "strongly agree". Examples of statements included are "*I can easily feel this kind of feedback*", "*I think this kind of feedback is ticklish*", "*I can barely feel this kind of feedback*", "*I like the feedback*" and "*I think this kind of feedback hurts physically*".

A qualitative analysis shows that overall 88% of the users stated a neutral or positive attitude towards the system. Of these, men and left-handed individuals, in particular, perceived the system positively, rating it with an average value of 4.23 on the Likert scale to the questions regarding how much they liked the system. On the other hand, women and right-handed people seem to perceive the stimuli 4,95% more intense than men. This information though is not statistically significant.

## 4 Discussion

The results of the magnitude estimation and ESSI ratings show that electrovibration stimuli using 80Hz sine waves produced the highest ratings. An input signal of 80Hz

actually creates a 160Hz Coulomb force vibration on user's finger. Therefore, 160Hz provides the most intense sensations.

In terms of amplitude, we observed a linear change of intensity in a logarithmic scale. Hence we can suggest that the perceived intensity is logarithmically proportional to the supplied signal.

We selected a set of test participants by carefully maintaining a balance between their gender and the handedness. The analyzed results of magnitude estimation did not show any significance with both factors. In the ESSI test, gender did not show any significant difference but the right-handed participants rated the stimuli as slightly more intense than left-handed participants. Serrien *et al.* [23] found that the left hemisphere, which is strongly linked with the right hand, is dominant when controlling complex skills of either hand, especially in visuomotor conflict situations. In both cases (our study and the one presented by Serrien *et al.*) participants had to perform continuous drawing movements. This may explain the possible differences in electrovibration intensity perception between left and right-handed users.

## 5 Conclusions

This paper provides a brief overview of electrovibration as tactile feedback, and describes an experimental setup for a preliminary investigation of the perceived intensity of modulated friction created by electrovibration. We introduced and used a fixed 6-point Effect Strength Subjective Index (ESSI) as a measure of generic sensation intensity, and an open magnitude scale. The early results of the experiment indicate that, for continuous sinusoidal signals, there are significant differences in intensity perception for different amplitude/frequency combinations. The highest intensity was found at 80 Hz, which corresponds to 160 Hz as friction modulation. These results are evident in both the magnitude estimation data and the ESSI ratings.

In follow-up studies it will be necessary to recruit participants from a larger age range. The study reported here was conducted with 26 participants and all were between ages of 20 to 36. Hence there was not enough variation in age to analyze the result with respect to aging. In terms of touchscreen feedback, in order for electrovibration intensity to be used as a design parameter effectively, it will be necessary to combine it with other parameters to see if there are any negative effects when used in combination. Furthermore, future studies will investigate electrovibration stimuli with other combinations of modalities such as audio and visual.

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