Overview Electrotactile Feedback for Enhancing Human Computer Interface

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Abstract. To achieve effective interaction between a human and a computing device or machine, adequate feedback from the computing device or machine is required. Recently, haptic feedback is increasingly being utilised to improve the interactivity of the Human Computer Interface (HCI). Most existing haptic feedback enhancements aim at producing forces or vibrations to enrich the user’s interactive experience. However, these force and/or vibration actuated haptic feedback systems can be bulky and uncomfortable to wear and only capable of delivering a limited amount of information to the user which can limit both their effectiveness and the applications they can be applied to. To address this deficiency, electrotactile feedback is used. This involves delivering haptic sensations to the user by electrically stimulating nerves in the skin via electrodes placed on the surface of the skin. This paper presents a review and explores the capability of electrotactile feedback for HCI applications. In addition, a description of the sensory receptors within the skin for sensing tactile stimulus and electric currents as well as several factors which influenced electric signal to transmit to the brain via human skin are explained.

1. Introduction

New and innovative Human Computer Interaction (HCI) technologies have recently attracted increased interest. This is mainly due to the proliferation of various interactive computing devices and applications including gaming, virtual reality, augmented reality, teleoperation, telepresence, sports and skill training systems, etc. (see [1] [2], [3]). To be effective, HCI requires the input device to be intuitive and user friendly and the output device to provide appropriate information or feedback to the user. Normally, the user input is delivered to the computer via a keyboard and mouse and information or feedback is received via a visual display and generated sounds. Recently, gesture based input devices that involve tracking the body, hands or finger movements, have been gaining attention over the conventional keyboard and mouse for certain interactive applications [4]. Similarly, 3D stereo head mounted displays and haptic feedback devices involving vibrating actuators or electro-mechanical forces have been developed to improve the interactivity of many applications (e.g. [5-6]).

The word of haptic comes from the Greek word ‘hapto’ which means to touch and handle objects. Touch sensing relates to stimuli on the skin and is what gives both humans and animals the ability to detect and classify objects that come in contact with the skin. Touch sensing is often referred to as tactile sensing by researchers who attempt to implement, enhance or facilitate touch sensing via electronic or mechanical means [7].
Adding 3D stereo perception and haptic feedback to the interface can help the user to gain a sense of being immersed in a remote or virtual environment and result to improved interactivity [8]. Most haptic feedback systems aim at enriching the user’s sense of touch making it possible to interpret or interact with the application, or a remote or virtual environment, more effectively.

Haptic interfaces use artificially induced haptic sensations to deliver information or feedback signals from a computer or a machine to the user. Haptic feedback can make it possible to simulate the tactile characteristics of a remote or virtual object (such as weight, texture, force, movement, etc.) via electro-mechanical or electronic means. These physical characteristics are difficult, if not impossible, to perceive visually. Since touch sensing is important for manipulating objects, haptic feedback can enable the user to operate a machine or a computer program with more agility and dexterity. Applications that make use of haptic interface are wide and expanding. Some prominent examples are: surgery training simulators [9], teleoperation of robots in hazardous environments [10] and VR applications [11]. These applications have haptic interfaces that can range from simple force feedback joystick devices with a single Degree of Freedom (DOF) [12], to more complex interfaces with multiple DOF [10].

Most haptic feedback systems are aimed at replicating certain natural tactile sensations and consist of force and/or vibrating electro-mechanical actuators coupled to the user with mechanical linkages or bulky garments. These systems are often difficult to setup and bulky to wear and can compromise the user’s movements and comfort. Furthermore, electro-mechanical haptic feedback systems are often custom built and configured for specific applications which can make it difficult to use the same haptic feedback system for different applications [13]. To overcome these drawbacks, the electrical signal was introduced to deliver information to the user. This paper reviews several methods and for transmitting information signals and its applications by the electrical signal.

Electrotactile feedback involves producing haptic sensations by electrically stimulating nerves in the skin via electrodes placed on the surface of the skin. They were initially developed for providing substitute visual perception to the blind [14]. Recently, electrotactile feedback has become recognised by some researchers as being simpler and more versatile than electro-mechanical feedback systems. The main benefits of electrotactile feedback is that it is inexpensive, it has no mechanical or moving parts and it can deliver a wide variety of sensations to the user by simply varying the electrical signal delivered to the electrodes [14].

To explain this in more detail and provide some understanding on the factors that influence the delivery of electrotactile feedback information to the brain, via neurons in the skin, the following section provides some background information on the human tactile sensory system.

2. The Human Tactile Sensory System

Compared to other sensory organs, human skin has the largest number of sensory receptors. Touch sensing actually combines several sub-modalities (e.g. pressure, temperature, texture, movement, pain, etc.) These tactile sensations from the skin are mediated by the somatosensory system which also processes sensory information from the epithelial tissues, skeletal muscles, bones, internal organs and the cardiovascular system. To understand the possibilities of any tactile feedback device, it helps to know the structure and functionality of skin, including the sensory nerves and receptors within the skin.

The two types of human skin are hairy skin and glabrous (or hairless) skin. Hairy skin has hair follicles and comprises almost 95 percent of human skin. Glabrous skin covers about 5 percent of the human body and has a thinner dermal layer, for increased touch sensitivity, and thicker epidermis without hair follicles. Glabrous skin also has a ridged appearance with circular patterns (like fingerprints), e.g. finger pads, lips, palms and the soles of feet [15].

Human skin is sensitive to several sensations, e.g. temperature, vibration, pressure or electric current/voltage. To accommodate these sensations, skin has a number of sensory receptors, namely, mechanoreceptors, thermoreceptors, nociceptors and proprioreceptors. Furthermore, mechanoreceptors can be divided into seven classes and thermoreceptors have two classes. In addition, there are four and
three classes for nociceptors and proprioceptors, respectively [16]. Electrotactile feedback works mainly on the mechanoreceptors. Table 1 lists the four major mechanoreceptors and their respective sensory modalities.

### Table 1. Skin Mechanoreceptors (adapted from [16]).

| Class           | Meissner’s Corpuscles | Merkel’s Cells | Pacinian Corpuscle | Ruffini Endings |
|-----------------|-----------------------|----------------|--------------------|-----------------|
| Sensory Correlate | Rapid Adapting Type I | Slow Adapting Type I | Rapid Adapting Type II | Slow Adapting Type II |
| Frequency range | 10-200 Hz             | 0.4-100 Hz     | 40-800 Hz          | 7 Hz            |

The following section presents certain related factors that can influence the design and control of electrotactile interfaces.

### 3. Electrotactile Sensory Substitution Methods

Electrotactile feedback has been shown to be capable of delivering a variety of tactile sensations [17]. Although it is not possible to replicate all the possible tactile sensations perceivable through the skin, electrotactile stimulation can provide a reasonable substitute in certain applications. There are a number of factors that can influence effective information transmission through the skin while minimising feelings of discomfort. In general, these factors are mainly related to the characteristics of the electro-neural stimulation parameters, the conductivity and location of the electrodes on the skin, and the properties of the skin.

#### 3.1 Electrodes

Chemical compounds can be produced by electrodes in an electrochemical process. For example, any electrolysis reactions in water might damage skin cells. Electrodes made of noble metals or conductive polymers may reduce or eliminate any electrochemical reaction [18]. The size of the electrodes can also be important. Small electrodes can generate higher density currents which can cause discomfort to the user. Electrodes with an area of 10mm² or greater have been shown to perform better than smaller electrodes [19].

#### 3.2 Waveform Stimulus

Square wave electrical pulses are more commonly used for electro-neural stimulation than sinusoidal waves due to their improved efficiency and ease of implementation. Most comparisons find no significant differences between the performances of these two waveforms [16,20]. However, biphasic stimulation may help prevent half-cell reactions and aid in preventing ions being absorbed from electrodes and conductive gels [21].

#### 3.3 Polarity

Some researchers have described the use of bipolar and unipolar signals for electrotactile stimulation (e.g. [22]). These results suggest different sensations can be produced by changing the polarity of the electrodes. A bipolar signal has an alternating current phase that is positive and negative. A unipolar signal only has a positive or a negative phase. Generally, bipolar signals are preferable in order to prevent skin irritation caused by the transfer of ions within axon membranes. Generating a negative pulse shortly after a positive pulse, or visa-versa, can also reduce polarisation caused by the first
stimulation. Studies suggest a delay of between 50-500μs can produce delayed depolarisation [23]. For unipolar signals, positive pulses tend to produce a lower sensory threshold and are more comfortable than negative pulses [23].

3.4 Frequency
Experiments conducted by Saunders [24] suggest that a frequency range between 2-100 Hz is the optimal for electrotactile stimulation. These frequencies are within the detectable range of all rapid adapting Type-I receptors and some slow adapting Type-I receptors [25]. Investigations by Collin [26], indicate that the perceptual response to a continuous pulse rate at frequencies higher than 60Hz results in fast adaptation, whereas, frequencies around 10Hz produce slower adaptation [28,29]. However, high frequency pulses in bursts can also produce slower adaptation.

3.5 Pulse Width
It has been shown that pulse widths between 50-150μs provide effective receptor stimulus [21,27]. Furthermore, Mortimer [20] have shown that there is an inverse relationship between the pulse width and the threshold current. Generally, to reduce the power consumption and to prevent potential harm to the user’s skin, it is preferable to keep the pulse width to a minimum. Experiments by Rollman [29] and Mortimer [20] suggest a pulse width around 100μs is optimal in terms of power consumption and receptor stimulation.

3.6 Burst Rate
Some researchers, e.g. [30], have shown that long continuous pulse trains, particularly at low power and higher frequencies, can cause rapid adapting Type-I receptors to become adapted to the stimulus. To prevent receptors from becoming adapted to stimulus, some researchers have opted for grouping pulses into bursts. For example, Kaczmarek has shown that short repeated bursts at a low rate (<15Hz) could produce good results at avoiding adaptation [27].

3.7 Pulses per Burst
The dynamic range and sensitivity of rapid adapting Type-I receptors can also be affected by number of pulses per burst, particularly at higher frequencies. For example, Kaczmarek [22], showed that increasing the number of pulses per burst beyond six can fail to provide any additional performance improvement. Kaczmarek’s results show that improved performance could be achieved with 200Hz pulses grouped into bursts of 6 pulses with a delay of 37ms per burst.

3.8 Modulation Method
The adaptation of receptors can also be avoided by modulating the frequency and/or the intensity of the electrical stimulus. For example, Szeto [31] conducted experiments on test subjects where various stimulus parameters were modulated including the polarity, frequency, intensity and the number of active electrodes. Apparently, identifying the position and/or the number of activated electrodes performed the best. Furthermore, test results with lower frequencies were better than results with higher frequencies [28].

3.9 Skin Features
Skin impedance and sensitivity can vary depending on its moisture content and location on the body. Generally, glabrous skin performs worse than hairy skin for electrotactile stimulation because of its thickness. This can make electrical conductivity difficult and individual receptors hard to target [20]. Glabrous skin is also found only on small inconvenient regions of the body, e.g. palms and the soles of feet. Moistening the skin with conductive gels prior to applying electrodes can also improve the electrical conductivity and reduce the possibility of painful sensations occurring as a result of current flowing directly through sweat glands [20]. The following section provides further examples of electrotactile haptic interfaces and a more detailed explanation of their implementation and operation.
4. Electrotactile Feedback Devices
Electrotactile feedback involves producing haptic sensations by electrically stimulating nerves in the skin via electrodes placed on the surface of the skin. The main benefit of electrotactile feedback, over vibrotactile or force feedback systems, is that there are no mechanical or moving parts and it can deliver a wide variety of sensations to the user that are not available with existing vibrotactile or force feedback systems.

With electrotactile feedback, the electrodes can also be placed on various body locations where more cutaneous sensory neurons are available, e.g. tongue [32], hands/arms [13], or abdomen [33]. Since the hands and fingertips have high neural density, they are often studied for delivering haptic information to the brain via electro-neural stimulation [34].

Electro-neural stimulation has been intensively studied for providing Tactile Visual Substitution (TVS) for the blind. For example, in the late 1990s, Kazmarek et al [32], proposed a Tongue Display Unit (TDU) for the blind. The tongue was used because it has high tactile sensitivity and spatial acuity. Additionally, the tongue is always wet and therefore provides good electrical conductivity and stable electrical properties.

Electro-neural stimulation is not commonly used for developing information feedback systems. Most haptic researchers traditionally use force and/or vibrotactile haptic interfaces, probably due to fears that electro-neural stimulation might cause pain and/or discomfort to the user. However, some researchers have recently attempted to develop haptic feedback systems using electro-neural stimulation mainly because of its success at providing substitute visual perception to the blind as well as the advantages it has over electromechanical interfaces, as explained in [14]; e.g. no mechanical components, low cost and increased bandwidth for interpreting information.

Another advantage of electro-neural stimulation is that the electrodes can be configured into compact arrays and used to implement electrotactile displays. These are mostly used for TVS systems, like the TDU. They have also been used for helping patients to recover from posture and balance-disorders such as Meniere’s disease and as a navigation aid [35]. Electrotactile arrays, like that used for the TDU, are typically comprised of 144 electrodes configured into a 12x12 matrix. These electrodes are generally made from gold-plated copper pads fixed to a flexible printed circuit polymer sheet.

Other researchers, e.g. Kajimoto et al, developed an electrotactile display system called the SmartTouch [36]. SmartTouch is a 4x4 matrix array made from 1mm diameter concentric stainless steel electrodes that can generate both pressure and vibration sensations. These sensations occur because the positive inner electrodes are designed to stimulate the Meissner’s corpuscles (near the surface) which are responsible for sensing pressure. The negative outer electrodes are meant for stimulating the deeper Pacini corpuscles, which are involved in sensing vibrations.

To explore the potential of electrotactile feedback, Daniel and Koren use hand gesture based input devices (such as Leap Motion or P5 data glove [4]) combined with electrotactile feedback for achieving more effective control and improved interaction of various computer controlled machines and applications for example teleoperation[37], VR [38], training [39], and controlled prosthesis hand [40]. This generally involves using hand and/or finger movements to operate a remotely located machine, or an agent in Virtual Reality (VR), while receiving haptic sensations from the electrotactile feedback system. The electrotactile stimulus is usually derived from real or virtual sensors mounted on a remote machine, or a VR environment. When used in conjunction with a 3D head mounted display, electrotactile feedback can help the user to feel more immersed within the remote or virtual environment and achieve more dexterous control of the machine or virtual agent.

5. Conclusions
The main benefits of electrotactile feedback is that it has no mechanical or moving parts, requires no-invasive surgery and can deliver haptic information to the user via a wide variety of sensations that are not available with existing vibrotactile or force feedback systems. These reason makes electrotactile feedback has a potential to enrich the HCI systems, to make the user more engaged with the system.
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