# **Background Reading**

## Research Literature

Due to the high concentrations of mechanoreceptors found on human fingertips, exploration of the fingertips ability to discriminate electrotactile stimulation at four points has been explored. It's noted that during testing, stimulation was delivered to the volar aspect, with varying electrode sizes, interelectrode spacings and stimulation frequency as the main factors. Discrimination of stimulated locations under this parameter was significantly above chance levels in all cases. It's incredibly prevalent to note that electrode size or stimulation frequency in this test it was not a significant influencer when considered separately [2].

These findings are reinforced in [14], when the percentage of participants hit at least 70 %, who of which could feel the stimulation when the pulse width or the pulse repetition frequency was varied. When verifying the percentage of participants who could differentiate tactile sensation, the adjustment of the pulse width or pulse repetition frequency increased the number of participants who could notice the difference to at least 60% no matter which factor was adjusted. It was therefore concluded that the higher the pulse repetition frequency the greater the number of participants who could notice the difference as the pulse width varied. And the wider the pulse width was, the greater the number of participants who could do so as the pulse repetition frequency varied.

However, results showed in [2] that increased electrode spacing significantly increased subjects’ ability to discriminate location of stimulated electrodes. Knowing this, it may be useful to investigate multi-channel electrotactile stimulation for sensory feedback of fingers. The work explored in [15], made efforts to find possibilities for two channel electrotactile stimulation through intermittent stimulation for better performance. This promoted the possibility for independent feedback of the forces of the fingers in question. By applying offset pulses, the stimuli of each channel would be recognised somewhat independently, and not get confused with each other. This would reduce the masking effect of simultaneous stimulation and improve recognition of the stimuli by users.

The spatial distribution of electrodes should be considered, as any force applied to a virtual object can be replicated if there is a selection of appropriate points of stimulation. For example, stimulation from a centre pin electrode can simulate the contact between the centre of the fingertip and an object edge. Whereas stimulation from one of the many pin outer electrodes can simulate the contact between an area of the fingertip’s surfaces of the base of a cylindrical object [7].

Several studies have measured the skin's ability to transfer electrical stimulation to mechanoreceptors and their fibres by delivering either pulse voltage across all, more commonly, regulated current through the skin surface [2]. Pulse width is an important characteristic in determining the amount of charge that is delivered to the skin. It also affects sensation of the electrical stimulation. The frequency of stimulation may also play a role in discriminating the location of a signal [2].

It is key to know that there are several mechanoreceptors in the human skin, that determine perception of contact with an object. And that each one of them have different sensitivities to tactile pressure and receptive field sizes. Regardless of the amount of force needed to stimulate the area. Electrical stimulation of the mechanoreceptors creates the same feeling as a physical stimulation. [9] [19]

As defined by Schroeder in [9], the basic principle of electrical stimulation is the application of an electrical potential difference to the surface of the skin via electrodes. The electrical balance across the nerve of membrane between the location of stimulation is disturbed, which can then trigger an action potential and the nerves that are in the area between the electrodes. As shown in Figure 1 the electrical potentials that are applied to the skin are defined by the parameters frequency (f), pulse width (pw) and amplitude (voltage or current). Nerve fibres respond uniquely dependent on the constraints of the applied pulses. Pulses with a shorter pulse width and higher current is necessary to create a response and pulse; whereas a long pulse width requires a lower amplitude [9].

Pulse Width

1/Frequency

Amplitude (Voltage or current)

***Figure 1***

When a short pulse is sent through, the sensory nerve response is defined by the sensory threshold. When applying higher currents above the sensory nerve threshold, or a longer pulse width, you can see muscle activation. Because of this, stronger pulses results can pain if the frequency of the stimulation is too high. If this happens nerves will fail to respond. This is because the refractory period can only be started after some time. It is mentioned in [20], that the maximum frequency for nerves to react is in the range of 4-5kHz.

Given that skin is multi layered, and as such provides natural resistive properties that could make it difficult to interpret test results. Electrical conductance in biologic tissue depends on the ion-permeability of the tissue in question [16]. Stratum corneum cells are densely packed lattice of layered corneocytes composed of relatively high resistivity keratin compared to other tissues in the body, such as muscle, bone and underlying dermal tissue. The stratum corneum makes up the protective barrier of skin exposed to the environment [10][17].

Dry stratum corneum is an almost impermeable tissue, but wet corneum, by virtue of aqueous channels between the keratin plates and possibly between the keratin fibrils, is rather freely conductive [16]. This is also covered in [18] where the flow of aqueous electrolyte depends on the applied voltage magnitudes. The electrical resistance and capacitance of the skin are extrinsic properties; hence, skin impedance is dependent on effective electrode area against the stimulated skin surface which in turn depends on applied force between skin to electrode interfacing. In contrast, the resistivity of sub dermal skin tissue and other soft tissues is shown to be mostly invariant of frequency and amplitude (as seen in [2]) and is much lower and constant spatially in value compared to the stratum corneum. Whereas for the stratum corneum square wave electronic pulses evidence indicates that the electronic resistivity of the stratum corneum layer decreases almost inversely with increasing current amplitude [10].

The germinative layer by virtue of the large interstitial canaliculi in which even protein molecules have been observed to migrate is rather freely conductive, but the granular layer possible constitutes a barrier as does the dermo epidermal junction, where the cells are tightly joined. The membranes of these cells may be relatively ion-impermeable as are those of many cells because of the lipid or protein content [16].

Due to the uniqueness of the user’s biology, the interpretation of skin conductance depends on the conditions on which it will be measured. It can be seen in [7] to achieve additional electrical conductivity between the electrodes on a skin. A small amount of conductive gel was applied to the fingers of the users prior to the fitting of the gloves. This would enable the testers to get around some of the individual biological characteristics of the users and bypass any natural skin impedances.

A mention of mechanoreceptors in the skin in [19] details records of four types of sensory endings:

* Meissner corpuscles
* Pacinian corpuscles
* Merkel cell-neurite complexes
* Ruffini endings

The assembly of each of these receptors discusses the different characteristics of nerves. If we look at the Meissner Corpuscles, it is said that for adequate tactile sensation, only an isolated stimulus in a localised area is needed as they are sensitive to light stokes on the skin. Whereas the Pacinian corpuscle needs an abrupt automatic sensation to activate the receptors. To reduce or avoid activation of nerve trunks and muscles, stimulation can be delivered using concentric electrodes. This arrangement will generate surface currents, thereby avoiding unnecessary activation of the deep sensory motor structures [3]

And mentioned above, it can be said that the shape and surface area have an impact on the surface effect of the sensation received on the skin. Circular electrodes have a better user experience than rectangle electrodes, this is because the current can peak at the corners of the rectangular electrodes. An electrode with a surface area of 1 or above 100 can cause a prickly or painful sensation. [9]

Looking into different papers, there is a debate on which waveform is the most beneficial for electrotactile feedback. In a test performed in [21] three waveforms were evaluated on a concentric electrode.

* Monophasic wave, with a pulse of 150 at 0.5 – 0.25 mA
* Wave with alternating phase pulse of 150 at 0.5 – 0.15 mA
* Biphasic, pulses at 10kHz at 0.5 – 0.15 mA

After achieving a comfortable tactile threshold for each participant, by altering the current amplitude. An average current level was chosen, with the charges per pulse being within ±4dB despite the waveforms being very different. Intermittent inspections of the stimulation zone showed small reactions in the epidermis. The results showed biphasic stimulation as the most comfortable, because of its shorter pulse width required, a greater current amplitude to produce an equivalently strong sensation, and therefore produced a greater amount of transient skin reddening and other reversible changes. Monophasic stimulation with longer pulses required the least amount of current for satisfactory sensation and produced the least amount of transient skin reddening. The alternating phase stimulation came in second. So overall no major safety concerns can be considered in choosing the type of waveform. Just the application of said waveform. This experiment can be reinforced by the stimulation test carried out in [14] where it was confirmed that a certain percentage of participants experienced a change in ‘comfort’ levels as the pulse repetition was changed.

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